16:28:52 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 09/22/93

Active

Project #: E-25-631 Cost share #: E-25-318 Rev #: 10
Center # : 10/24-6-R7019-0A0 Center shr #: 10/22-1-F7019-0A0 OCA file #:
Work type : RES
Contract#: DDM-9001733 Mod #: ADM. REVISION Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 47.041
Main project #: PE #: N/A

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
UMEAGUKWU I C MECH ENGR (404)894-7411
JARZYNSKI J MECH ENGR (404)-

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 900901 to 940831 (performance) 941130 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	270,431.00
Funded	0.00	270,431.00
Cost sharing amount		72,625.00

Does subcontracting plan apply ?: N

Title: LASER PHASED ARRAY GENERATION OF ULTRASOUND FOR ON-LINE WELD QUALITY CONTROL

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Tyndall 894-4820

Sponsor technical contact	Sponsor issuing office
MARVIN DEVRIES (202)357-7676	THOMAS NOEL (202)357-9602
NSF 1800 G STREET, N.W. WASHINGTON, D.C. 20550	NSF 1800 G STREET, N.W. WASHINGTON, D.C. 20550

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : NSF supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
ISSUED TO CORRECT ERROR IN FRINGE CATEGORY.

DR-478
8/22

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/14/95

Project No. E-25-631 Center No. 10/24-6-R7019-0A0

Project Director UMEAGUKWU I C School/Lab MECH ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-9001733 Contract Entity GTRC

Prime Contract No.

Title LASER PHASED ARRAY GENERATION OF ULTRASOUND FOR ON-LINE WELD QUALITY CONT

Effective Completion Date 940831 (Performance) 941130 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REQUIREMENT.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 02/14/95

Project No. E-25-631 Center No. 10/24-6-R7019-0A0_

Project Director UMEAGUKWU I C___________ School/Lab MECH ENGR______

Sponsor NATL SCIENCE FOUNDATION/GENERAL______________________________

Project # E-25-N01 PD UMEAGUKWU I C Unit 02.010.126 T
GRANT # DDM-9001733 MOD# BR DTD 9-22-93 MECH ENGR *
Ctr # 10/24-6-R-7019-0A1 Main proj # E-25-631 OCA CO JLB
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
LASER PHASED ARRAY G
Start 900901 End 940228 Funded 24,950.00 Contract 24,950.00

LEGEND
1. * indicates the project is a subproject.
2. I indicates the project is active and being updated.
3. A indicates the project is currently active.
4. T indicates the project has been terminated.
5. R indicates a terminated project that is being modified.

E-25-631

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

29-MAY-91

Dr. Suren Rao, D
Manufacturing Machines & Equipment
Division of Design and Manufacturing
System's Engineering
National Science Foundation
1800 G. Street, N.W.
Washington, DC 20550

RE: *Continuing Grant Increment "Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control, Grant No. DDM 9001733*

Dear Dr. Rao:

This is to request a continuing grant increment for the above referenced proposal. Thank you for your support of the referenced proposal, and we look forward to working with you this coming year.

Sincerely,

Charles Umeagukwu
Assistant Professor

PRELIMINARY REPORT
NSF GRANT NO. DDM-9001733

Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control

Submitted to

Division of Design and Manufacturing
System's Engineering
National Science Foundation
1800 G Street, N.W.
Washington DC 20550

Submitted by

Charles Umeagukwu

GEORGIA INSTITUTE OF TECHNOLOGY
The George W. Woodruff School of Mechanical Engineering
Atlanta, Georgia 30332-0405

May 1991

LASER PHASED ARRAY GENERATION OF ULTRASOUND FOR ON-LINE WELD QUALITY CONTROL

ABSTRACT

The current research work investigates the use of optical fiber arrays to enhance laser generation of ultrasound. Experimental and numerical directivity patterns are being investigated for optical fiber arrays generated longitudinal, shear, and surface waves. Comparisons of the directivity patterns for a single light source and for the fiber array are being conducted for each of the above waves. This research is limited to sound generation in the thermoelastic (linear) range. The optical fiber array can be used to control both the directivity and the type of elastic wave generated by the laser light. The noncontact fiber array generation can be combined with a noncontact electromagnetic acoustic transducer (EMAT) or laser doppler receiver to achieve a system for ultrasonic on-line inspection and control of manufacturing processes. The above technique for sound generation and reception is particularly useful in hostile and hard to reach environments. Plans are underway to (1) conduct some experiments and analyses to determine array gains, and (2) conduct experiments and analyses of sound propagation through simulated weld pool.

DISCUSSION OF RESULTS

The primary goals as set forth in the original proposal for this work were to (1) study and develop a noncontact ultrasonic NDE system, with laser phased array for generating the ultrasound, and an EMAT as a receiver, and (2) study the application of the laser phased array to on-line control of the depth of weld pool penetration and porosity in a gas metal arc welding (GMAW) process. To this end, the research conducted, so far, under this grant has been very successful.

The work completed so far include (1) a single source generation of longitudinal, surface and shear waves, (2) optical fiber array generation of longitudinal, surface and shear waves, and (3) shear wave generation by means of reverse array. The discussions below include experimental and numerical results.

The longitudinal and shear wave directivity patterns clearly indicate that for inspect purposes, the receiving transducer should be placed at 60° and 30° angles respectively. There is a close agreement between the experimental and numerical directivity patterns for the longitudinal and shear waves. The experimental directivity pattern for the surface wave has been measured, but the numerical calculations are yet to be performed. The array effect as demonstrated in the array gain, is not fully realized in the work performed so far. This is because the sum of the light energy delivered by the array is the same as that of a single source. In order to completely achieve the array effect, each fiber of the array must carry the same light energy as that of a single source. The use of a large diameter (0.0254 m) piezoelectric transducer (PZT) may have caused some signals to cancel each. This may be the cause of the slight difference between the experimental and numerical directivity patterns. The experimental verification of reverse array, indicates that the array enhances the generation of ultrasound in forward direction.

The discussion presented here is a summary of six months research effort. Two publications resulting from this effort are listed below. Copies of the publications are attached.

Charles Umeagukwu, Jacek Jarzynski, Nick DeRidder and Jr-Syu Yang, "Laser Generation of Ultrasound Using Optical Fiber Arrays," Invited presentation, 121st Meeting: Acoustic Society of America, Baltimore, Maryland, April 1991.

DeRidder, Nick, Yang, Jr-Syu, Ume, Charles, and Jarzynski, Jacek, "Noncontact Optical Fiber Phased Array Generation of Ultrasound for Nondestructive Evaluation of Materials and Processes," Submitted, Journal of Ultrasonics, May 1991.

LASER GENERATION OF ULTRASOUND USING OPTICAL FIBER ARRAYS

Charles Umeagukwu, Jacek Jarzynski
Nick de Ridder and Jr-Syu Yang
The George W. Woodruff School
of Mechanical Engineering
Georgia Institute of Technology

Acknowledgement

The authors would like to acknowledge the support of the Manufacturing Machines and Equipment program of the NSF, which provided funding for this research, under Grant No. DDM-9001733.

PRESENTED (Invited Paper)

121st Meeting: Acoustical Society of America,

Baltimore, Maryland, April 1991

ABSTRACT

Laser Generation of Ultrasound for Process Control Using Optical Fiber Arrays. Charles
Umeagukwu, Jacek Jarzysnki, Nick de Ridder, and Jr-Syu Yang (School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405)

This paper reviews recent work on the use of optical fiber arrays to enhance laser generation of ultrasound. Experimental and numerical directivity patterns are presented, obtained using optical fiber arrays to generate longitudinal, shear, and surface waves. Comparisons of the directivity patterns for a single light source and for the fiber array will be presented and discussed for each of the above waves. Also shown will be some experimental results on array gains. This discussion will be limited to sound generation in the thermoelastic (linear) range. The optical fiber array can be used to control both the directivity and the type of elastic wave generated by the laser light. The noncontact fiber array generation can be combined with a noncontact EMAT or laser Doppler receiver to achieve a system for ultrasonic on-line inspection and control of manufacturing processes. The above technique for sound generation and reception is particularly useful in hostile and hard to reach environments. [Work supported by the National Science Foundation.]

OVERVIEW AND RATIONALE

Laser generation of ultrasound:

Advantages

Non-contact; allows continuous scanning.

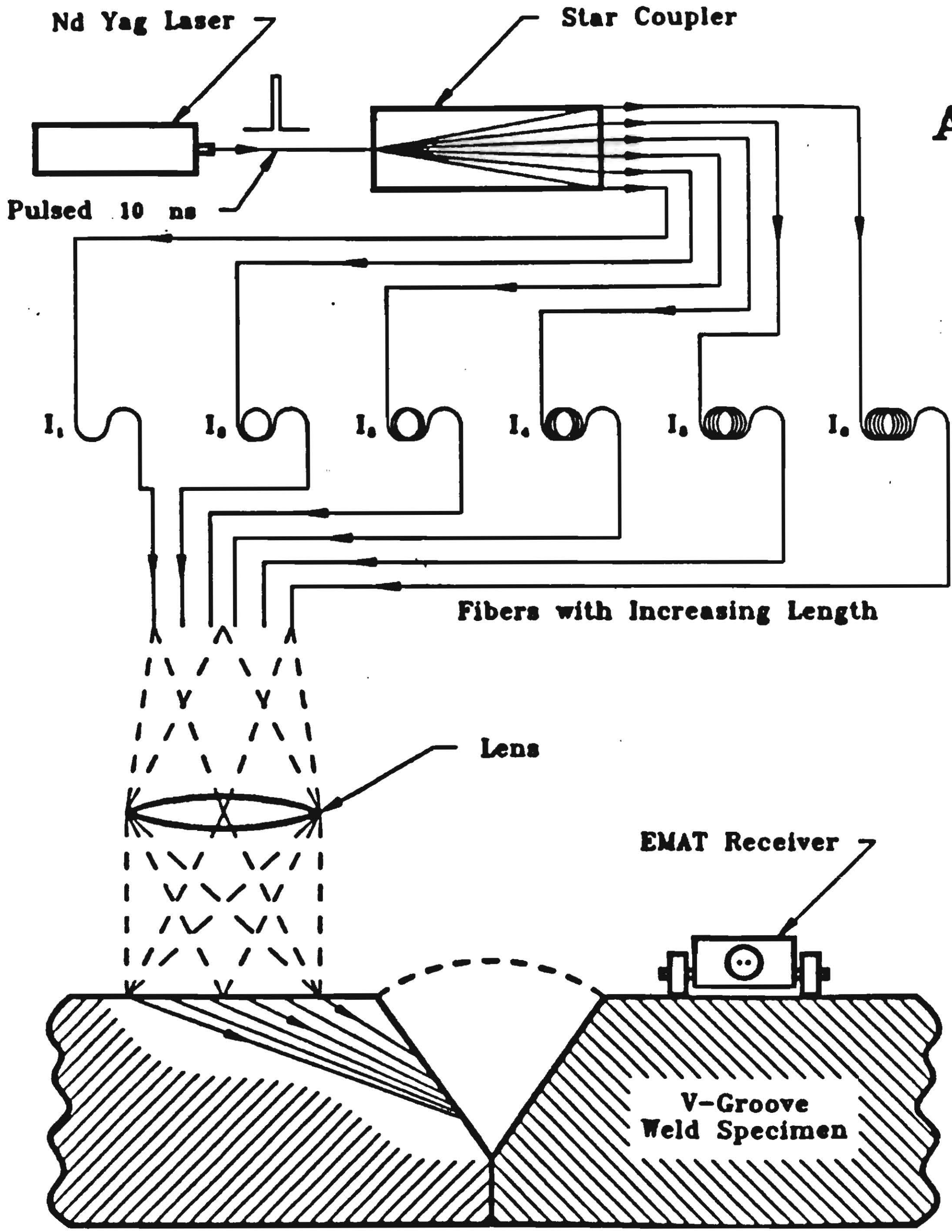
Can be used in difficult environments; on surfaces at high temperatures.

Disadvantages

Low conversion efficiency from light energy to ultrasound.

The efficiency for laser generation of ultrasound can be increased by using a fiber optic array—experimental results and estimates of performance for the fiber array are presented—potential applications to on line quality control of welding are discussed.

EXPERIMENTAL SETUP
APPLICATION TO WELDING



REFERENCES

Primbech and Bickel, "Apparatus for Producing Ultrasonic Waves in a Workpiece", Patent Application, 1983.

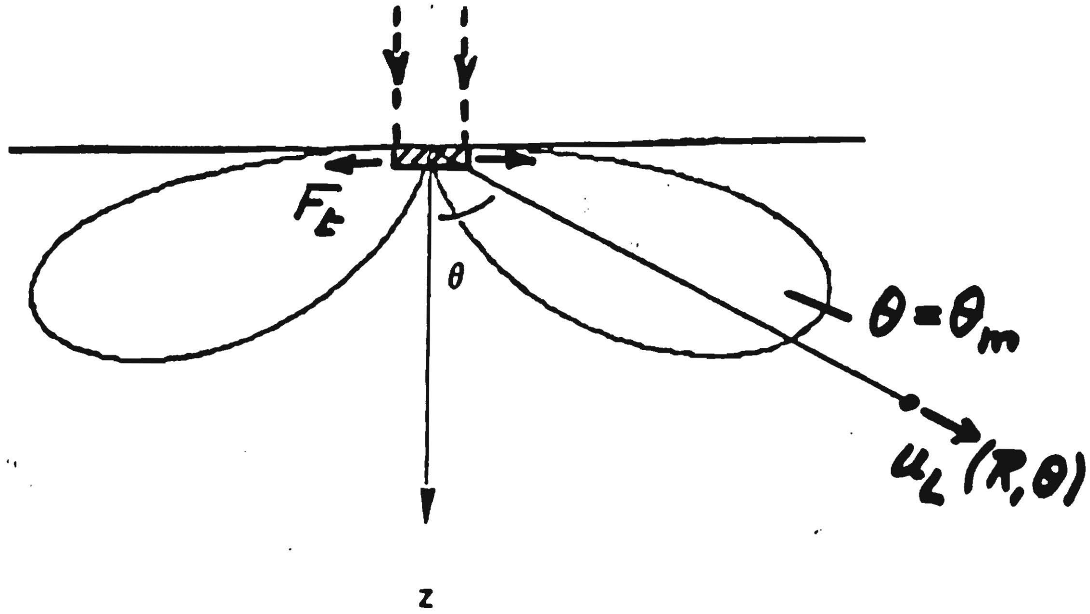
Vogel, Bruisma and Berkhout, "Beamsteering of Laser Generated Ultrasound", Proc. Ultrason. Int. 87 Conf., 1987. (longitudinal waves)

Jarzynski and Berthelot, "Application of Acousto-optic Light Modulation to the Laser Generation of Ultrasound", J.Acoust. Soc., Vol. 82, S20 (1987).
(longitudinal waves)

Ing, Fink and Gires, "Directivity Patterns of a Moving Thermoacoustic Source in Solid Media", submitted for publication to IEEE, 1991.

Umeagukwu, Jarzynski, de Ridder and Yang, unpublished 1991.
(longitudinal, shear and surface waves)

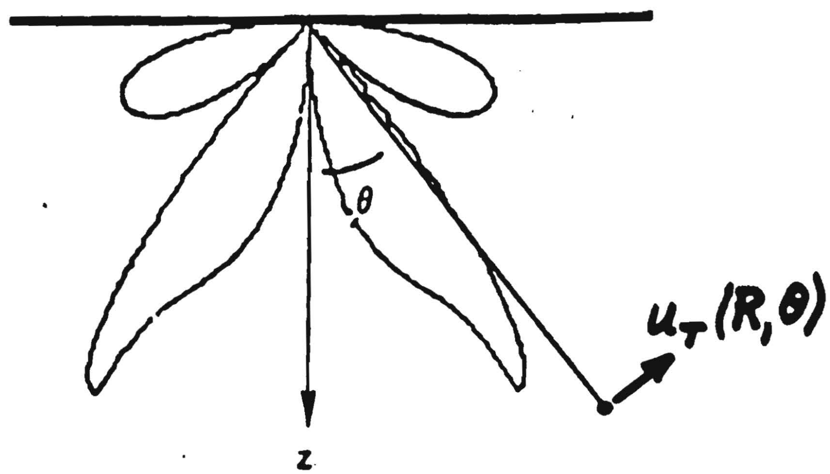
DIRECTIVITY OF LONGITUDINAL WAVES GENERATED BY A SINGLE LASER BEAM



$$u^t{}_L(R,\theta,t) = \frac{F_t}{2\pi(\lambda+2\mu)} \quad \frac{\sin 2\theta \,.\, \sin\theta \left[\left(\frac{k_T}{k_L}\right)^2 - \sin^2\theta\right]^{\frac{1}{2}}}{D(\sin\theta)} \frac{e^{-i k_L R}}{R} \,.\, e^{i2\pi ft}$$

$$D(\beta) = \left[\left(\frac{k_T}{k_L}\right)^2 - 2\beta^2\right]^2 + 4\beta^2 \left[1-\beta^2\right]^{\frac{1}{2}} \left[\left(\frac{k_T}{k_L}\right)^2 - \beta^2\right]^{\frac{1}{2}}$$

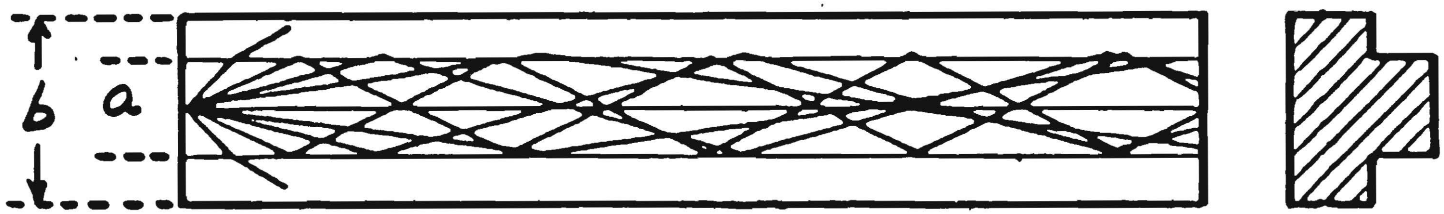
DIRECTIVITY OF SHEAR WAVES GENERATED BY A SINGLE LASER BEAM



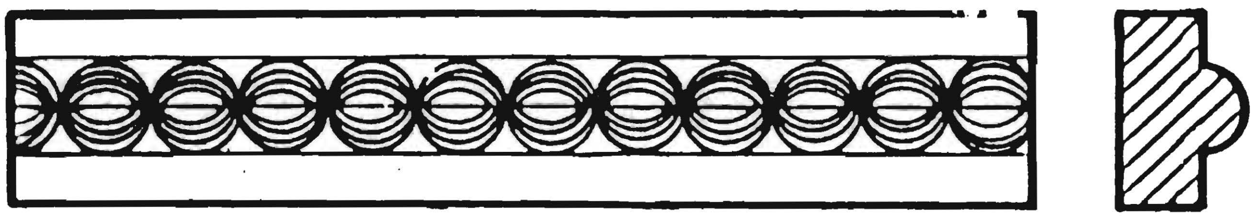
$$u^t_T(R,\theta,t) = \frac{F_t}{2\pi(\lambda+2\mu)}\left(\frac{k_T}{k_L}\right)^3 \frac{\sin 4\theta}{D\left(\frac{k_T}{k_L}\sin\theta\right)} \frac{e^{-i k_T R}}{R} \cdot e^{i2\pi ft}$$

$$D(\beta) = \left[\left(\frac{k_T}{k_L}\right)^2 - 2\beta^2\right]^2 + 4\beta^2\left[1-\beta^2\right]^{\frac{1}{2}}\left[\left(\frac{k_T}{k_L}\right)^2 - \beta^2\right]^{\frac{1}{2}}$$

PROPERTIES OF MULTIMODE OPTICAL FIBERS



MULTIMODE FIBER (STEPPED INDEX)



MULTIMODE FIBER (GRADED INDEX)

<u>Present work</u> — $a = 100\,\mu m$, $b = 140\,\mu m$

light intensity in the fiber $I = 3.2\ MW/cm^2$

Maximum intensity for the <u>thermoelastic regime</u>

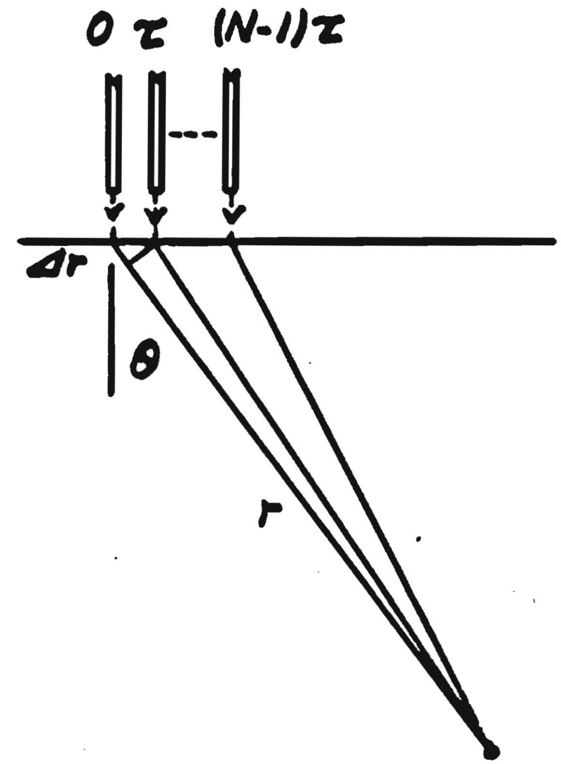
$\underline{I_m \simeq 10\ MW/cm^2}$

<u>Multimode fibers</u> — max $a = 2000\,\mu m$, max $I = 5 \times 10^4\ MW/cm^2$

FIBER OPTIC PHASED ARRAY

Particle displacement in the far field

$$u(r,\theta) = AD_1(\theta)\frac{e^{-i(kr-\omega t)}}{r}\Big(1 + e^{-i(k\Delta r - \omega\tau)}$$
$$+ e^{-i(k2\Delta r - \omega 2\tau)} + \cdots + e^{-i(k(N-1)\Delta r - \omega(N-1)\tau)}\Big)$$



The array term is

$$e^{-i(N-1)q}\frac{\sin Nq}{\sin q}$$

$$q = \frac{\pi d}{\lambda}(\sin\theta - \sin\phi)$$

ARRAY DIRECTIVITY FACTOR

The directivity of the fiber optic phased array is,

$$D(\theta, \phi) = D_1(\theta) \times D_a(\theta, \phi)$$

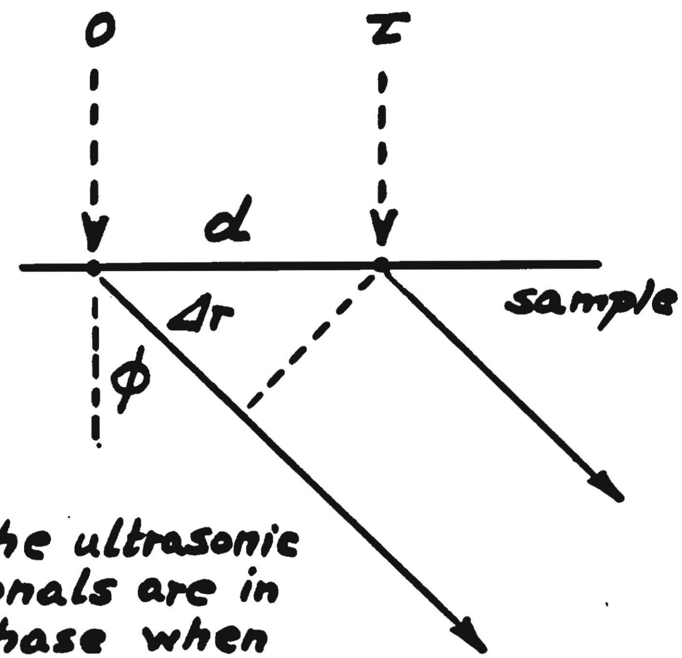
where the array term is

$$D_a(\theta, \phi) = \frac{\sin Nq}{\sin q}$$

$$q = \frac{\pi d}{\lambda}(\sin\theta - \sin\phi)$$

ϕ is the direction of maximum array gain

$$\sin\phi = \frac{\Delta r}{d} = \frac{c\tau}{d}$$



The ultrasonic signals are in phase when

$\Delta r = c\tau$

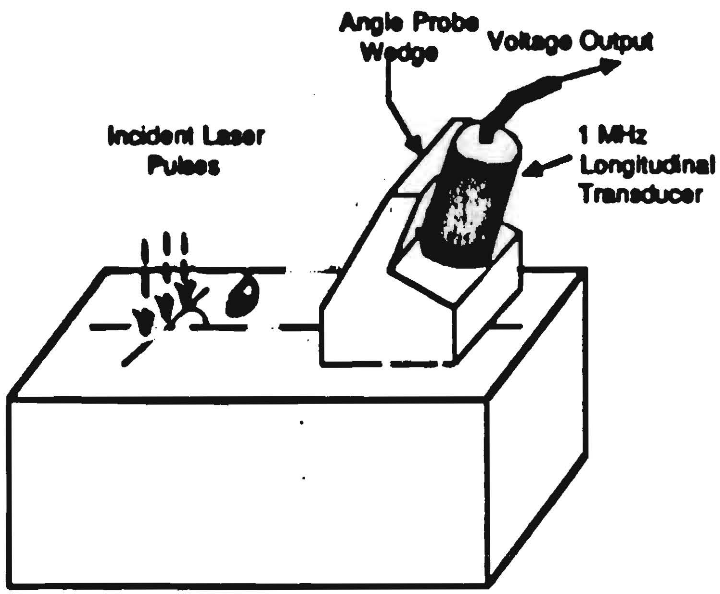
c - speed of longitudinal or shear waves in the sample

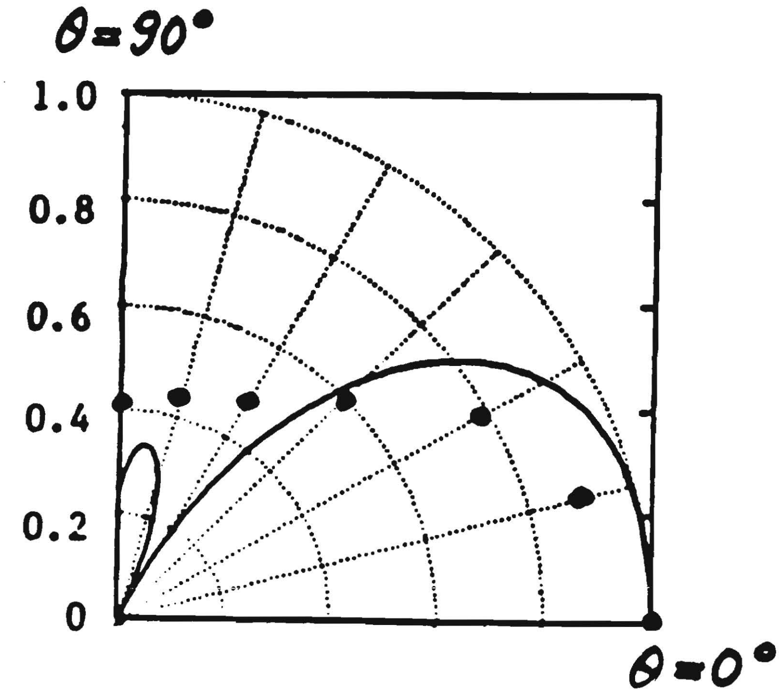
Fiber length increment = 30 m , $\tau = 0.15\ \mu sec$

$d = 1\ mm$

ARRAY BEAM STEERING–SURFACE WAVES

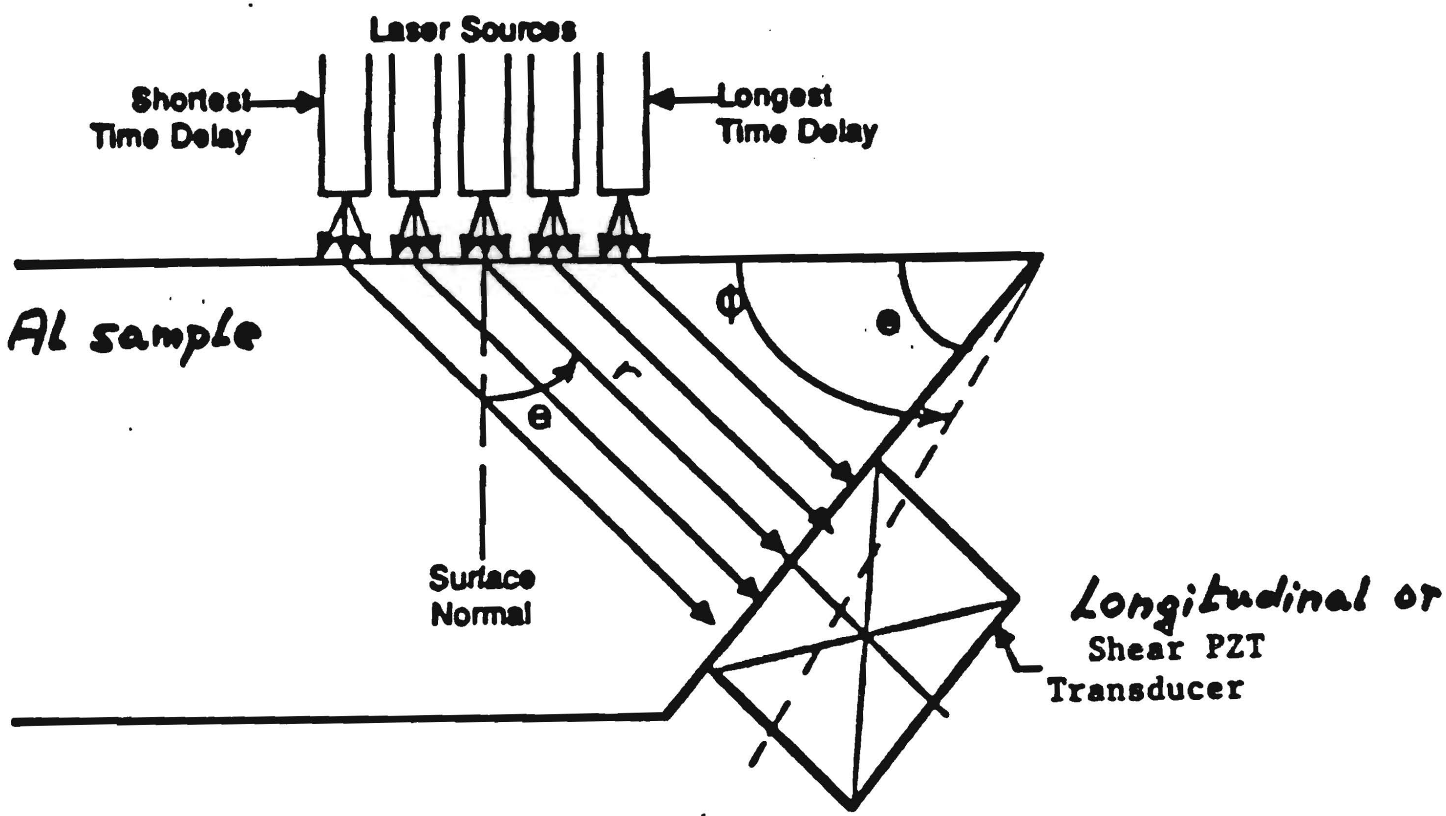
YAG laser , 100 μsec pulse, 1kW power level during pulse



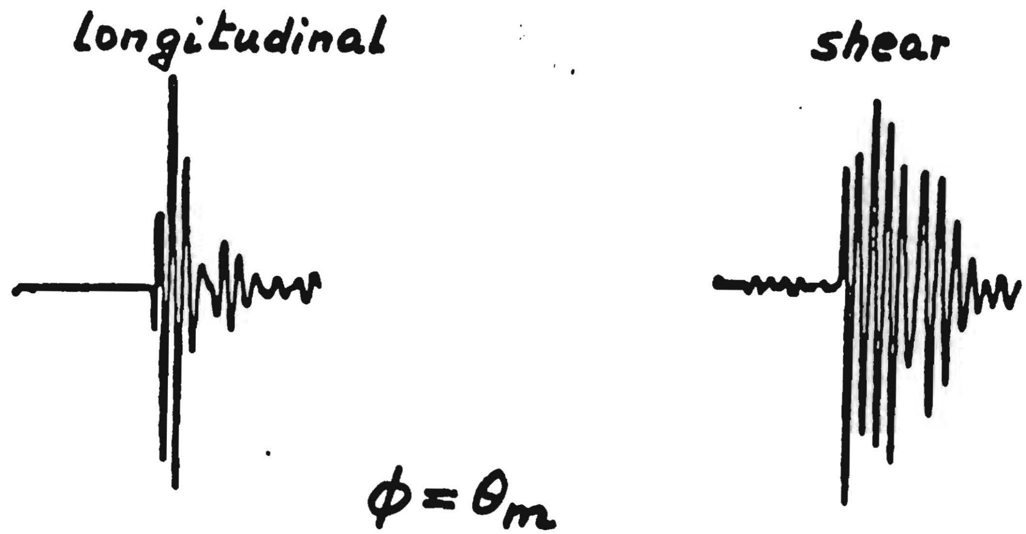


$D_1(\theta) = 1$

EXPERIMENTAL SETUP FOR MEASURING DIRECTIVITY PATTERNS



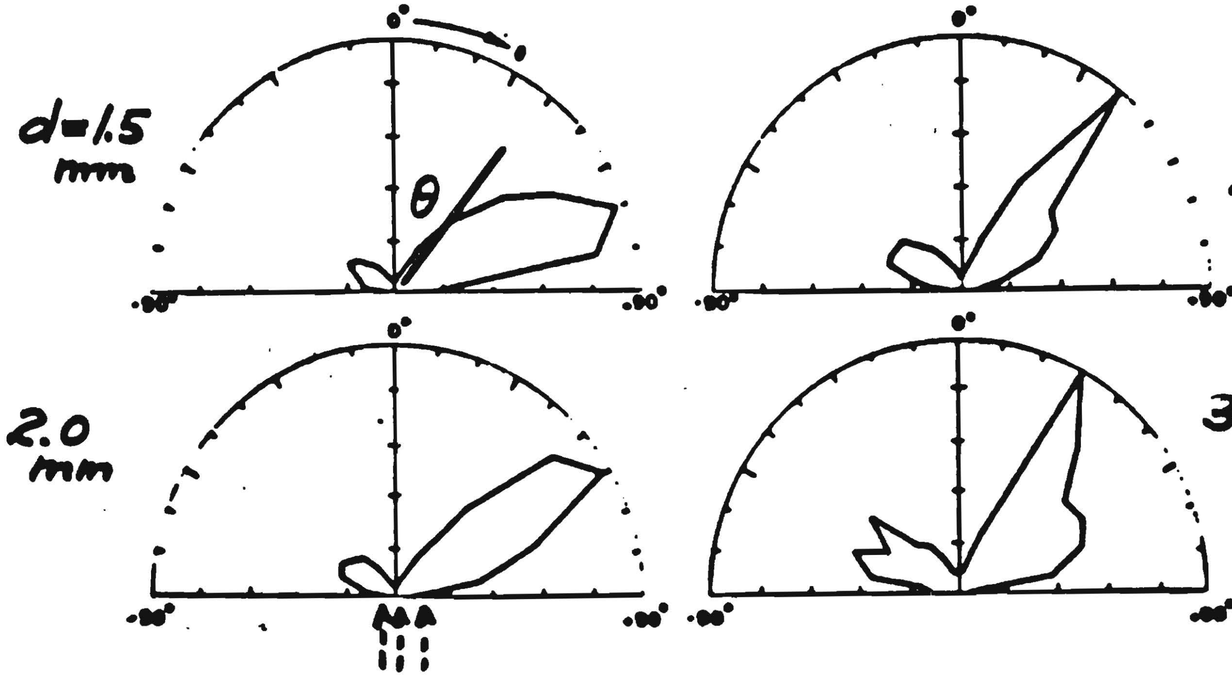
ULTRASONIC SIGNALS GENERATED WITH A FIBER ARRAY



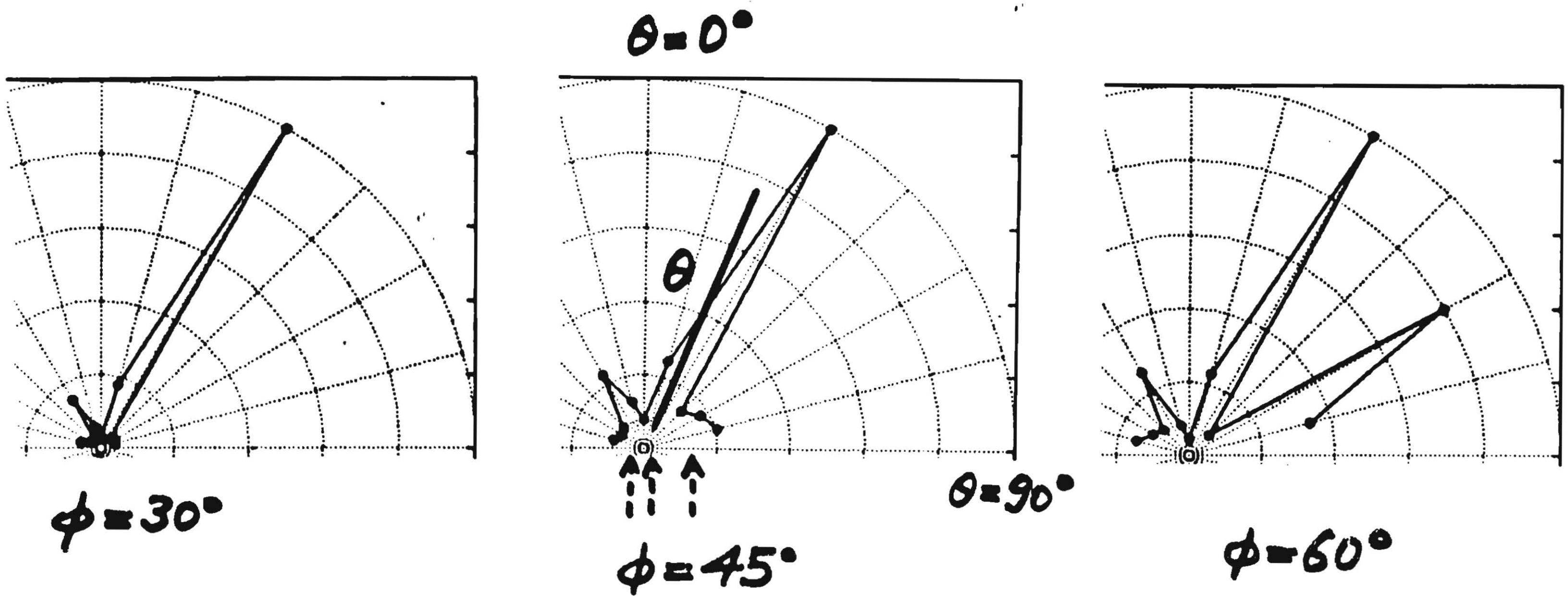
ARRAY BEAM STEERING–LONGITUDINAL WAVES

(Vogel et al. YAG laser, Q switch, 15 ns light pulse)
Al sample

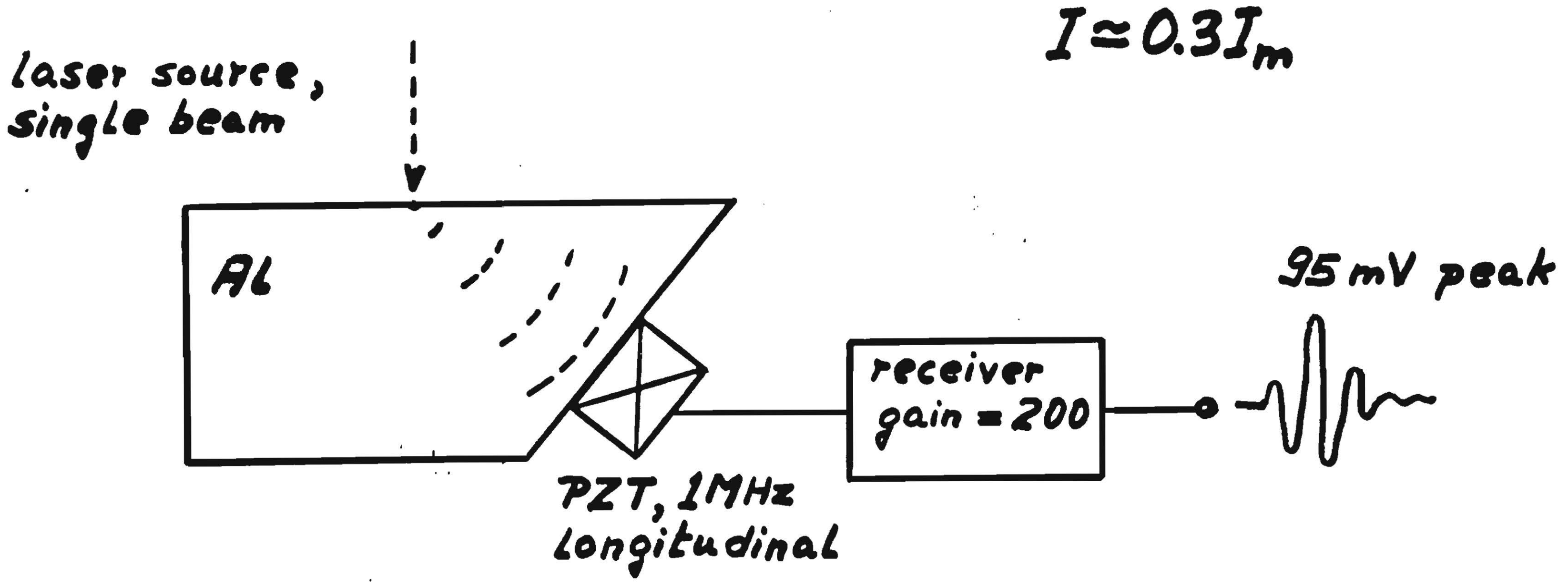
$f_0 = 5 MHz$
$\Delta f = 1\text{-}10 MHz$

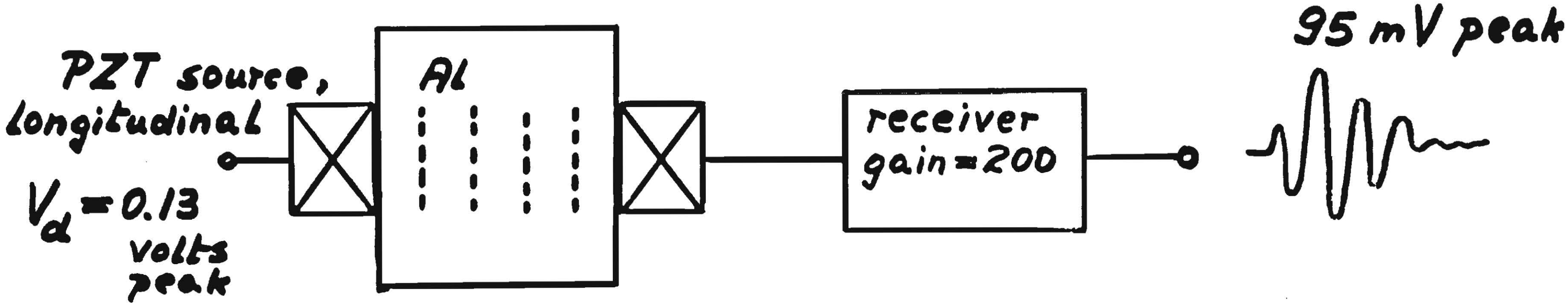


ARRAY BEAM STEERING–SHEAR WAVES

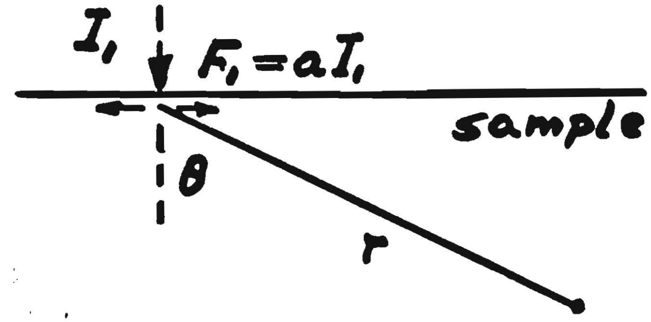


COMPARISON OF THE LASER SOURCE OF ULTRASOUND WITH A PZT SOURCE



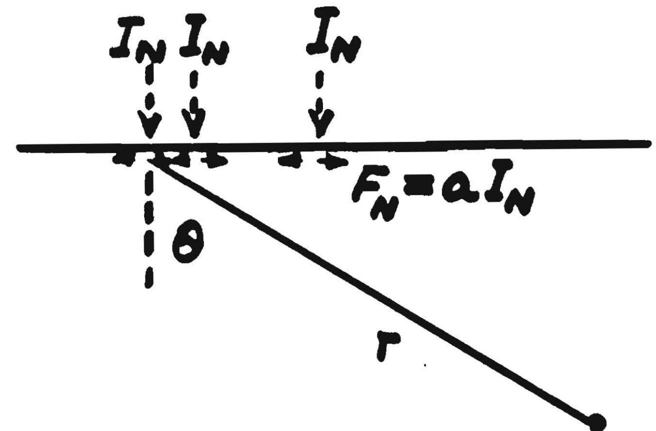


ESTIMATE OF THE GAIN FACTOR OF AN OPTICAL FIBER ARRAY



Single beam,

$$|u_1(r,\theta)| = \frac{CI_1}{r} D_1(\theta)$$



Array,

$$|u_N(r,\theta)| = \frac{CI_N}{r} D_1(\theta) \frac{\sin Nq}{\sin q}$$

$$\text{Gain } G \equiv \frac{|u_N(r,\theta)|}{|u_1(r,\theta)|} = \frac{I_N}{I_1} \frac{\sin Nq}{\sin q}$$

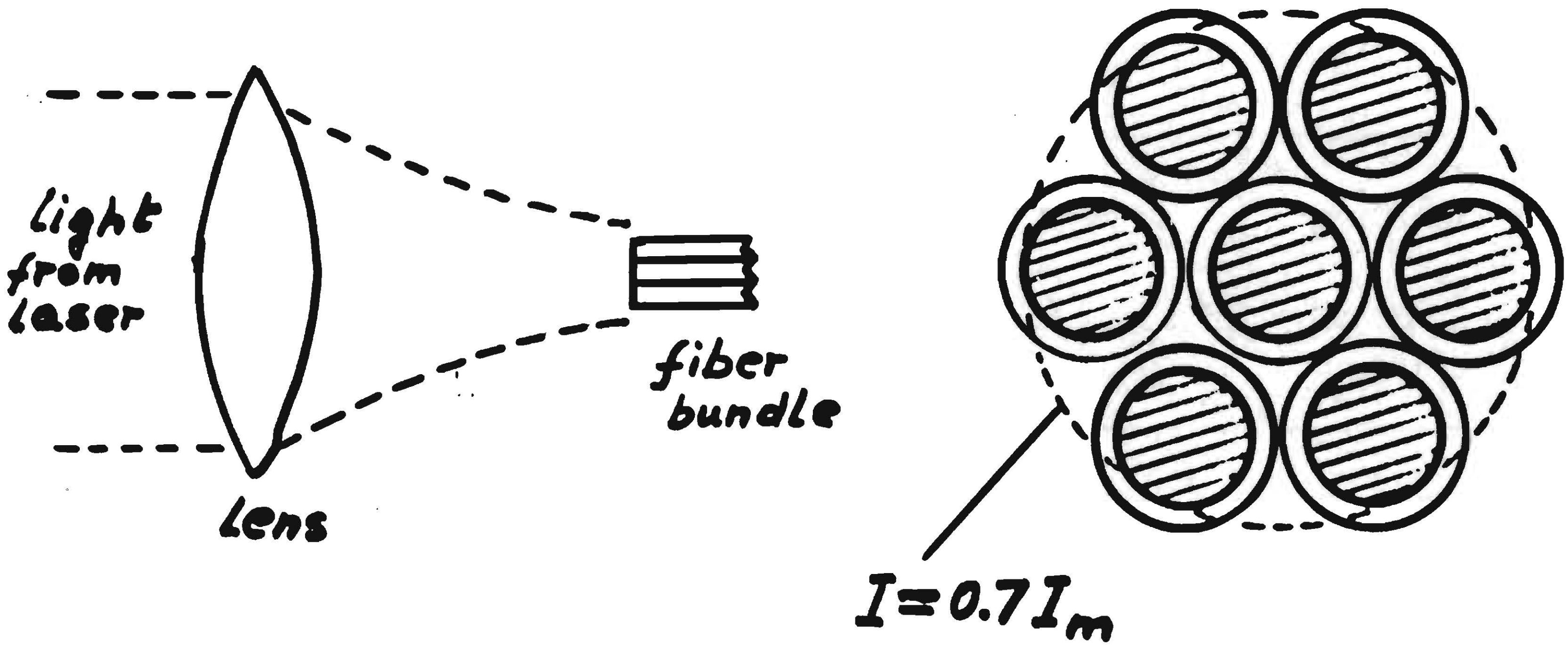
Maximum when $\theta = \phi$, $q \to 0$, $G = \frac{I_N}{I_1} N$

when $I_N = I_1$, $\underline{G = N}$

Present work — $N=5$, $I_N = \frac{1}{N} I_1$, $G = 1$

WAVE	MEASURED G	CALCULATED G
Longitudinal	1.19	1
Shear	1.18	1

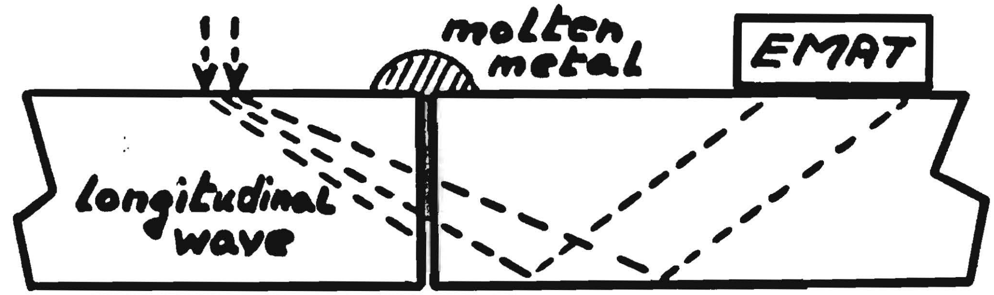
COUPLING OF LASER LIGHT INTO MULTIMODE FIBERS



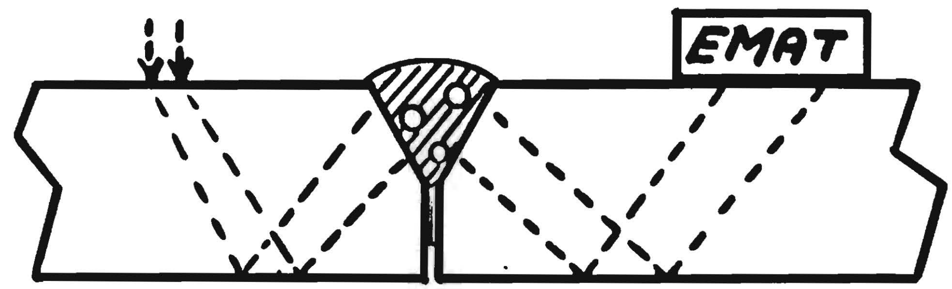
APPLICATION TO ONLINE QUALITY CONTROL OF WELDING

Parameters which could be monitored with ultrasound

1. Depth of penetration of the molten metal.



2. Air bubbles trapped in the weld.



<u>MEASUREMENTS</u> ⟷ <u>THEORETICAL MODEL</u>

- Time of flight.
- Amplitude.
- Frequency spectrum.

Ray approximation.

Form function for scattering by compliant sphere.

CONCLUSIONS

The basic concept, and directivity characteristics, of an end-fired optical fiber array for laser generation of ultrasound have been demonstrated for longitudinal, shear and surface waves.

It is estimated that an increase of 15–20 dB in the level of the generated ultrasound can be achieved with a fiber array. Further experimental work is needed to verify this estimate.

NONCONTACT FIBER OPTICAL PHASED ARRAY GENERATION OF ULTRASOUND FOR NON-DESTRUCTIVE EVALUATION OF MATERIALS AND PROCESSES

by

DeRIDDER, N., and YANG, J. (Graduate Assistants)

and

UME, C., AND JARZYNSKI, J.

George W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0405

(404) 894-7411

The use of non-contact laser techniques for generation of ultrasound has extended the limits of the application of the traditional ultrasonic techniques. Laser generation techniques can be used in hostile environments (e.g. high temperature, chemical etc.), and hard to reach areas, where the use of the traditional contact sensing is not practical.

Control of beam direction and focusing of the generated ultrasound is of major importance if maximum sensitivity is to be achieved for inspection purposes. We have focused our effort on increasing the sensitivity of non-contact ultrasonic technique. The approach taken is to use an optical fiber phased array to generate ultrasound instead of a single laser source. This method of sound generation is demonstrated experimentally, by using five optical fibers to deliver light pulses from Nd-YAG laser, and using a piezoelectric transducer as a contact receiver. The results of the shear wave directivity patterns obtained using this technique will be presented, and compared with that of a single source.

I. INTRODUCTION

Ultrasonic techniques are widely used for nondestructive evaluation (NDE) of materials and processes. For many uses in these areas a noncontact inspection tool, such as ultrasound, is desired. This is because most of these materials and processes involve high temperatures and often are corrosive in nature. A noncontact ultrasonic inspection is possible by generating ultrasound with a laser phased array and detecting the resultant surface vibration with a non contact receiver. The use of a laser phased array to generate ultrasound will lead to a new technique that is particularly useful for many industrial applications. This approach promises the emergence of noncontact ultrasonic sensors for NDE that will facilitate measurements of residual stress, internal temperature, velocity, defects, debonded areas, thin-film (not possible with conventional transducer techniques), surface modification, texture, interfaces, and elastic constant where uncertainties due to transducer bonding currently enforce a limitation in accuracy. This technique also permits detection of the molten metal/solid interface of the weld pool for the purpose of controlling the depth of penetration and flaws (cracks, pores, inclusions); sensing and control of high temperature material processes such as welding and solidification; determination of microstructural variables such as grain size; estimations of thickness and liquid depth; and inspections of corners, edges, curved surfaces, and objects at elevated temperatures. In addition, laser phased array generated ultrasound serves as an acoustic source with excellent repeatability.

Control of beam direction and focusing is of major importance in ultrasonic inspection of materials and processes in order to obtain maximum sensitivity for the detection of defects. Most studies, so far, of noncontact laser generation of ultrasound have used a single laser beam. A serious handicap in the use of a single laser beam for ultrasonic generation is the inability to control the ultrasonic beamwidth and beam direction. In addition, many optical systems are rather bulky, which limits their applications in hard-to-reach areas. The optical fiber phased array offers the possibility to control beamwidth, direction and focusing. The optical fiber phased array for beam control has several advantages over the existing noncontact generation methods. These advantages include (1) greater efficiency. Compared to ultrasound generation with a laser beam, the laser phased array increases the amplitude of the generated ultrasound in two ways. First, the array concentrates the ultrasonic energy over a relatively narrow range of directions (as opposed to the spherical spreading from a single beam). Second, in the region of linear, thermoelastic generation of ultrasound, the maximum intensity of the light beam is limited to below the threshold for damage of the sample surface. With a laser phased array, each fiber can transmit the maximum light intensity, and the total light energy transformed to ultrasound is increased by the number of fibers in the array. Other advantages include (2) The ability to transmit the ultrasound in a specified direction. (3) Preferential generation of one type of wave motion, such as the surface (Rayleigh) wave, shear wave, or longitudinal wave. (4) Less Complex. (5) Tremendous flexibility in achieving virtually any desired source configuration on the surface of the sample, and (6) Readily deployable.

Chapter II of this manuscript presents an indepth review of the techniques of sound generation. The description of the experimental setup is presented in Chapter III. Chapter IV contains a detailed presentation of single source generation of shear wave. In Chapter V, optical fiber generation of shear wave is described, while Chapter VI presents shear wave generation by means of reverse array. The conclusions of the experimental results are presented in Chapter VII.

II. SOUND GENERATION USING A LASER SOURCE AND AN OPTICAL FIBER PHASED ARRAY

The generation and subsequent propagation of ultrasound by the absorption of an intense laser pulse is now a relatively well understood process. For low absorbed fluxes, the surface where absorption occurs never exceeds its melting temperature and the source of ultrasound is then a transient dilatation. The stress associated with this dilatation is for the most part below the elastic limit, and this mode of generation is therefore referred to as thermoelastic [23]. The thermoelastic source radiates both shear and longitudinal energy enhancement with a thin layer of oil. At higher fluxes, the surface temperature rise is capable of exceeding the vaporization temperature. Atoms leave the surface at high velocity imparting a momentum to the substrate which is the source of ultrasound. This mode of generation is referred to as ablation, and enhances longitudinal wave generation.

In many situations, it is desirable to generate ultrasonic waves in a solid sample without having any transducer directly in contact with the surface of the sample under investigation. Such circumstances may arise, for instance, in the area of nondestructive testing of materials that are situated in unfriendly environments (e.g., very hot, or highly radioactive, or corrosive). The initial work of White [23] in 1963 showed that bulk waves could be generated by a harmonic heat flow on the surface of the sample. Since then, Aindow et al. [24] have shown that longitudinal, shear, and Rayleigh waves could all be excited by illuminating the sample under investigation with a short Q-switch YAG laser pulse. The literature on the laser generation of ultrasonic waves has grown extensively in the last decade because of the versatility of the method for many different applications (See, for instance, Refs. [25-31] and the review papers by Birnhaum and White [32], and by Hutchins and Tam [33].) One issue that has been addressed by many researchers is that of an optimum source configuration on the surface of the sample [34]. Cielo et al. [35], for instance, have proposed to illuminate the surface with an annulus of light in order to produce a strong signal at the focal point. They have reported a gain of more than 20 dB at the center of the annulus by using their convergent wave technique instead of a standard direct illumination technique. Ash et al. [36], and Royer and Dieulesaint [37] have used a periodic mask over the surface of the sample with a periodicity of a Rayleigh wavelength in order to force the generation of Rayleigh waves on the surface of the sample. Zolotov et al. [38] have used a Q-switched YAG laser pulse of 100 ns at a repetition rate of 10-50 Hz with a line source configuration on the surface of the sample.

More recently, Addison et al. [39] have investigated in detail the principles of ultrasonic array synthesis using laser beams, and what performances can be anticipated from these arrays. Yet another idea which has emerged fairly recently [40] consists of using optical fibers to guide the laser light, because they offer a tremendous flexibility in achieving virtually any desired source configuration on the surface of the sample. Optical fibers can also be used as time delays for properly phasing the heating taking place on the surface of the sample, therefore creating an array effect that improves in a particular direction the signal-to-noise ratio of the laser generated wave. Phased arrays offer the possibility to control beamwidth, direction and focusing. Although such an idea resulted in a patent [40] in 1983, it seems that the only published experimental data appeared in a publication by Vogel et al. [41] These investigators presented experimental results of the directivity pattern of a longitudinal wave. The other published material on phased array was by Jarzynski et al. They investigated the use of proper phasing between the acoustic signals received at the transducer to enhance the ultrasonic signal in a particular direction [42].

Vogel et al. used a Q-switched Nd-YAG laser operating in a pulse mode producing a short light pulse of 15-ns duration. The ultrasonic signal generated is thus very broadband, with a center frequency above 5MHz. The investigators presented experimental results of the directivity patterns for a longitudinal wave only. They used five optical fibers in this investigation.

Jarzynski et al. used a 1-W cw argon-ion laser and the light intensity was amplitude modulated using an acousto-optic modulator (Bragg cell). Thus the length of the light pulse is controlled by the drive signal to the modulator, which allows generation of an ultrasonic signal with narrower bandwidth and with a lower center frequency (1MHz). This study demonstrated experimentally how laser phased array enhanced the received longitudinal wave only. The receiver was a 1 MHz piezoelectric transducer. Only two optical fibers were used in this investigation.

III. DESCRIPTION OF THE EXPERIMENTAL SETUP

This chapter presents a detailed description of the experimental apparatus as shown in Figure 1. The basic experimental configurations used in this research consisted of a Nd-YAG laser, a multi-strand optical fiber array, an optical laser-fiber coupling assembly, a piezoelectric ultrasonic transducer, a photodetecting trigger circuit, test specimens, a digital storage oscilloscope for data collection, and a laser power meter. Two alternate systems were used for these experiments with the only difference being in the number of array elements used. The star coupler is replaced by a single fiber during a single source experiment.

A. Nd-YAG LASER

The laser source used to generate ultrasound in these experiments was a series Two-45 Neodynium Yag Laser purchased from General Photonics Corporation of Chatsworth California. The principal wavelength of this laser is at 1.064 micometers, with a natural oscillating line width of approximately 0.4 angstroms (about 10 GHz).

The laser was operated at full multimode pulsed output which produced a uniform and circular output beam with a maximum pulse power of 1 kilowatt (Average, 1 watt). The Two-45 laser is excited by a Zenon arc lamp with a continuously variable pulse rate of 0.5

to 10 Hertz. The nominal pulsewidth in normal operating mode is 100 microseconds. The beam diameter emitted from the two-45 laser is approximately 5mm with a beam divergence of 7 milliradians (the full angle including 85% of the total power output).

The two-45 laser is also available with a Q-Switching option which can increase the power output into the Magawatt range and reduce the pulse width to the nanosecond range. This option was not utilized in this research, though future plans related to this research do include experimentation with Q-switching for increased signal generating efficiency.

B. LASER/OPTICAL FIBER COUPLING ASSEMBLY

Focusing the laser light into the fibers, and splitting the laser energy were the two key considerations in coupling the laser course with the array delivery system. To accomplish the coupling, the laser beam was first focused into a single fiber using a microscope objective lens, and then the beam was split equally into multiple fibers using a device known as a star coupler.

Microscope Objective Lens

Coupling of the light emitted from the laser into a single fiber was accomplished using a Newport model M-20X achromatic microscope objective lens. The focal length of this microscope objective lens is 8.3 mm, with a numerical aperture (NA) of 0.40.

The fiber used in these experiments had a numerical aperture of 0.29, representing a half angle of acceptance of only 16.85 degrees. The critical alignment of the center of the fiber core with the focal point of the microscope objective lens was accomplished using a precision 3-axis positioner made by Line Tool Company of Allentown, Pennsylvania.

Star Coupler

Using the microscope objective lens, the laser light was focused into a single lead of a 6 x 6 star coupler manufactured by Canstar Inc., of Toronto, Canada. This particular star coupler features six receiving fiber strands and six emitting strands. The principle of operation behind a star coupler is simple. As light enters through any of the receiving fibers, a crystal arrangement at the center of the device splits the beam into equal parts to be passed on through the emitting fibers. For this star coupler, the receiving and emitting ends of the coupler were interchangeable. A diagram of the star coupler is shown in Figure 2.

The star coupler comes equipped from the manufacturer with one meter of fiber for each of the receiving and emitting strands. One emitting fiber from the star coupler was used to activate the trigger circuit, as discussed later. Therefore, a maximum of five array fibers were available for transport of laser energy to the test surface. These five emitting ends were spliced to the array fibers.

Array Spacing Control Assembly

For these experiments, the receiving end of the array was fixed rigidly in the optical laser-fiber coupling assembly. However, in order to control variable ultrasonic generation directivities, the emitting ends of the array elements required an adjustable spacing system. The array spacing control assembly shown in Figure 3 was fabricated specifically for this purpose.

The spacing control assembly was designed to hold six optical fibers, each attached to a 0.813 mm (0.032 in) thick steel plate. To precisely control the spacing between each fiber, metal shim stock was placed evenly between each plate. Then, the steel plates separated by shims were attached to the base of the assembly using a single bolt. Two dowel pins were used to control alignment of the plates.

The spacing control assembly shown is very simplistic by design. However, for experimental purposes this design is very accurate and easy to operate. For a real time system, this device would be too cumbersome and slow to adjust. Future research involving the application of the phased array system will likely require the design of a dynamically variable automatic spacing control system. For example, the real time inspection of a weld pool might demand a system using several different directivity patterns per cycle. This flexibility could require changing the array spacing several times per second.

C. PIEZOELECTRIC ULTRASONIC TRANSDUCER

As stated in the introduction, one key objective of this research is to develop a non-contact system for generating ultrasound in metals. This is especially useful in situations where conventional ultrasonic transducers can not be used. One of the most popular conventional ultrasonic generators is the piezoelectric transducer (PZT). This type of transducer is usually capable of both generating and detecting ultrasound. In this investigation, the function of ultrasonic generation is performed by the optical fiber, but detection is accomplished by means of PZT type transducer. In this research, PZT was used preferentially over non-contact methods because their sensitivity is substantially higher than most non-contact methods and they are consistent and easy to use. Future research in this area will include using an alternative ultrasonic detector to couple with the laser generation to comprise a totally non-contact system. The transducer used in the research was a 1 MHz shear wave transducer, manufactured by Panametrics. The diameter of the receiving element is 2.54 cm (1 inch).

D. TEST SPECIMENS

The solid body sample shown in Figure 1 was typical of the samples used to study preferential generation of shear waves in specific directions. These specimens were constructed of thick aluminum blocks with various angles, θ, cut at one end. Seven specimens were used with θ varying from 0° to 75° by increments of 15°. The laser arrays were directed onto the free surface of a given block and the 1 MHz shear PZT transducer was placed at the angled end of the sample. The Panametrics SWC coupling compound was also placed at the interface of the transducer and the sample to provide a coupling between the two surfaces.

E. DATA ACQUISITION AND ANALYSIS SYSTEM

The primary data acquisition component used in this research was a Tektronix model 2430 digital storage oscilloscope. Other components of the data acquisition system included an electronic amplifier, a photodetecting trigger circuit, and a personal computer for graphical computer analysis of sensor data.

Digital Storage Oscilloscope

A Tektronix 2430 digital storage oscilloscope was used to acquire and store all ultrasonic sensory data for this research project. The oscilloscope was synchronized with the pulsing laser through the use of a photodetecting trigger circuit. In relation to this research, the most useful feature of this oscilloscope is that input sensory data can be averaged over as much as 256 sampling intervals. This feature proved very useful at increasing the signal to noise ratio by overcoming distortion attributed to drifts in the trigger signal from the photodetecting circuit.

Another important feature of this oscilloscope is that as many as four sample sweeps could be sorted internally for down loading to a personal computer for data analysis. For each experimental situation, test data was recorded in this manner and subsequently transferred to an IBM personal computer for analysis via MATLAB software

Electronic Amplifier

Prior to input into the oscilloscope, the voltage output of the PZT was amplified using a Metrotek model MR101A receiver/amplifier. This amplifier features variable gain ranging from 1 to 63 dB, and variable low pass filtering from 0.5 to 4 MHz. The features of this unit proved valuable for increasing the signal to noise ratio.

Photodedecting Trigger Circuit

In collecting data for the ultrasonic experiments, the synchronization between the laser pulse signal and the oscilloscope acquisition system was found to be of extreme importance. The ultrasonic pulses studied in this research were on the order of 1MHz to 5MHz. At these frequencies, a drift of even a few microseconds can amount to a large portion of a pulse period. Therefore, when averaging acquired signals, a drifting pulse can greatly distort data results.

For these experiments, a photodetecting trigger was devised to generate an electrical signal each time a pulse was emitted from the laser. These electrical signals were in turn used to trigger the oscilloscope for data acquisition. The primary element of the trigger device was a PIN photodiode, United Detector Technologies model 119-1. A schematic drawing of the trigger circuit is shown in Figure 4.

Laser light was delivered to the photodetector through one lead of the star coupler. Though this practice reduced the amount of array fibers available, the convenience and non-intrusive capture of the source events proved an important consideration in overall system performance. Furthermore, the use of an optical fiber to deliver a signal to the trigger circuit allows such a system to incorporate a trigger delay in the same manner as the delays discussed for the array fibers. Moreover, use of a fiber allows the trigger circuit to be placed in a remote location, reducing environmental damage and interface. Both these features could be very beneficial in the real time control system application of this technology.

Laser Power Meter

Accurate adjustment control of the laser strength in each fiber element of the system was accomplished through the use of a Coherent model C25 pyroelectric joule meter (power meter). This unit emits a voltage proportional to the laser strength when placed in the path of the laser beam. The voltage output of the power meter was monitored and recorded via the digital oscilloscope.

Computer Analysis Using MATLAB Software Package

An IBM PC was used for data analysis. The single source and array source data were analyzed in the PC by using a MATLAB software package. In both the single and array sources, the maximum amplitude was used to normalize the rest of the data. The MATLAB was also used to generate hardcopies of the acquired waveforms which were downloaded from the oscilloscope.

IV. SINGLE SOURCE

A. EXPERIMENTAL PROCEDURES

A Microscope objective lens is used to focus the laser beam into a multimode fiber, and the power level is measured with a power meter (21.3 mJ). The laser beam is focused onto aluminum samples with varying block angle, θ, (θ varies from 0° to 75° in 15° increments) as shown in Figure 5. A 1 MHz PZT transducer is used to measure the sound pressure. For each of the aluminum blocks, the path length, r, from the source to the shear wave receiver is maintained at 1.5 inches, with the exception of θ = 75°, which is maintained at 2.5 inches, due to geometric constraints. In order to obtain statistically valid data, the oscilloscope is used in maximum averaging mode (256 samples are averaged), and five different readings are averaged to give a data point. The directivity patterns obtained for the shear wave are shown in Figure 6.

B. DISCUSSIONS OF THE RESULTS

Figure 6 shows that at block angle, θ = 30°, the strength of the signal is notably high. The presence of a grating lobe at θ = 45° is evident. There need to be data points at θ = 22.5° and θ = 37.5° to give the directivity plot a better definition. The value of the data point for θ = 75 is a little lower than the expected value. This is attributed to experimental setup and design error, which caused the receiving transducer to overlap the edge of the aluminum block. This caused the receiver to receive only part of the generated signal.

V. *OPTICAL FIBER ARRAY*

A. *EXPERIMENTAL PROCEDURES*

Single source generation of ultrasound is not very useful in certain inspection applications because the generated ultrasound comprises of all the different wave modes. Furthermore, the generated ultrasound spreads spherically from the source of its origination. Preferential generation of a particular mode of ultrasound, control of beam direction and focusing is critical in ultrasonic inspection if maximum sensitivity is to be achieved. An optical fiber phased array can generate an ultrasound of interest, control the beam width and direction, and effectively focus the beam if the beam path lengths are long enough.

The setup for the optical fiber phased array is shown in Figure 7. The interelement spacing controls the type of wave generated and its direction. A microscope objective lens is used to couple pulsed laser light to one of the six receiving fiber strands of the star coupler. A five element optical fiber array of increasing length (length difference of 60 m) is used with an interelement phase lag of 2.92×10^{-7}s. The sixth optical fiber carries the trigger signal. The five fibers are focused onto the surface of each of the six aluminum blocks with block angles (see Figure 7) varying from 0° to 75°, at 15° increments. A 1 MHz shear wave transducer is used to measure the transmitted ultrasound. The first peak-to-peak amplitude of the received sign (after 256 averages in oscilloscope) is a measure of the sound pressure. An average of five such sound pressure measurements represents a data point in the directivity plot.

Whenever the array is focused onto the surface of a block with angle, θ, it means that the spacing, d, for that array configuration is calculated based on that angle, θ. It also means that, that angle θ is equal to the steering angle θ_S, as shown in Figure 7. The other block angles (referred to as off-angles) are not equal to θ_S. In order to obtain a directivity plot when an array is focused onto the surface of a block with angle θ, the same array spacing, d, used for this particular block, will be used for the off-angle blocks. Typical shear wave signals obtained with five element fiber array focused onto a block with $\theta = \theta_S = 30$ are shown in Figure 8.

The directivity patterns obtained by focusing the array onto aluminum blocks with different steering angles are shown in Figure 9, superimposed onto the single source patterns. The total energy delivered by the array elements is 21.25 MJ (approximately the same as the single source).

B. *DISCUSSIONS OF THE RESULTS*

The directivity patterns of the array are shown in comparison with the single source directivity at approximately equal power levels. This graphical analysis uses the single course directivity as a standard for comparison with array directivity. The comparison is designed to show the beam steering trends, signified as the change in orientation of the major lobe(s) of the array sound field. These directivity patterns give an idea of the qualitative beam steering efficiencies of the various array configurations, and they graphically demonstrate the array gain. The most interesting feature of these results is the constant presence of a grating lobe at $\theta = 45^{\circ}$.

The beam steering efficiency of the shear wave array is demonstrated very well by the results shown in Figure 9. For interpretation of these results note that the total area under the directivity curve is not of critical concern since these patterns do not directly represent energy conservation. For each configuration, the array directivity, versus the single source, demonstrates significant shifts in the orientation of the major lobes. However, one interesting feature of these results is that not all of the configurations show a positive gain for the array sound pressure field. For $\theta = 15^{\circ}$ in Figure 9, the strength of the array field is found to be lower than the single source at all recorded directional angles, thus showing negative array gain. However, the major lobe of the array directivity pattern is shifted towards the beam steering angle as expected. Therefore the beam steering concept is proven to be effective.

Another interesting result from Figure 9 is that the array is not able to mask the naturally strong tendency of the shear wave near $\theta_S = 30$. Notice that for every configuration, the sound pressure at $\theta = 30$ is the strongest value in the data set. However, the array strength in each focused angle θ_S, is increased relative to the corresponding field strength at the same value of θ in the other configurations. This implies that there is phase addition at the beam steering angle, and there is phase cancellation at off-angles. This argument is graphically demonstrated in Figure 8. Figure 8 shows the effect of focusing the array onto a block with $\theta_S = \theta = 30^{\circ}$. One could see from the figure that the signals arriving at the surface of the PZT are in phase, for $\theta_S = 30^{\circ}$, but out-of-phase for the rest of the angles (off-angles).

VI. REVERSED OPTICAL FIBER ARRAY

A. EXPERIMENTAL PROCEDURES

The reversed array experiment is carried out, in order to demonstrate that, the array enhances, the directivity of the generated ultrasound in only one direction. The set-up is the same as in Figure 1, except that the fiber elements of the array are arranged in order of decreasing length (ie. the ordering of the fiber elements in Figure 1 is reversed). The same procedures that are described above for regular array are repeated for reverse array. For purposes of comparison, the directivity patterns for regular and reverse array are shown in Figure 9, for steering angles 30°, 45° and 60° respectively.

B. DISCUSSIONS OF THE RESULTS

In Figure 10, a comparison of the reverse array directivity patterns with that of the regular array reveals the effectiveness of using the array to control the beam direction. Obviously, the generated ultrasound interferes constructively in the forward direction, but interferes destructively in the backward direction. Figure 10 indicates that the maximum points in the directivity patterns of the reverse arrays occur at $\theta = -30^{\circ}$. One could also observe that the magnitude of each maximum point is directly proportional to its steering angle.

VII. CONCLUSION

The shear wave directivity patterns clearly indicate that for inspection purposes, the receiving transducer should be placed at a 30° angle. This is because the strongest signal strength is observed when the receiver is placed at 30° to a horizontal surface. It is also observed that the fiber array can selectively generate a particular ultrasonic wave of interest, in addition, it can control the direction of the generated ultrasound.

The array effect, as demonstrated in array gain, is not fully realized in this research. This is because the sum of the light energy delivered by the array is the same as that of a single source. To completely achieve the array effect, each fiber of the array must carry the same light energy as that of a single source. The receiving PZT is 0.0254m in diameter (1 in). The large diameter of the PZT caused the incident signals to be averaged over the entire surface of the PZT. This may have caused some signals to cancel each other. This argument becomes more credible, when you compare the wavelength of the shear wave to the diameter of the receiver.

One could also conclude that the array enhances the generation of ultrasound in forward direction.

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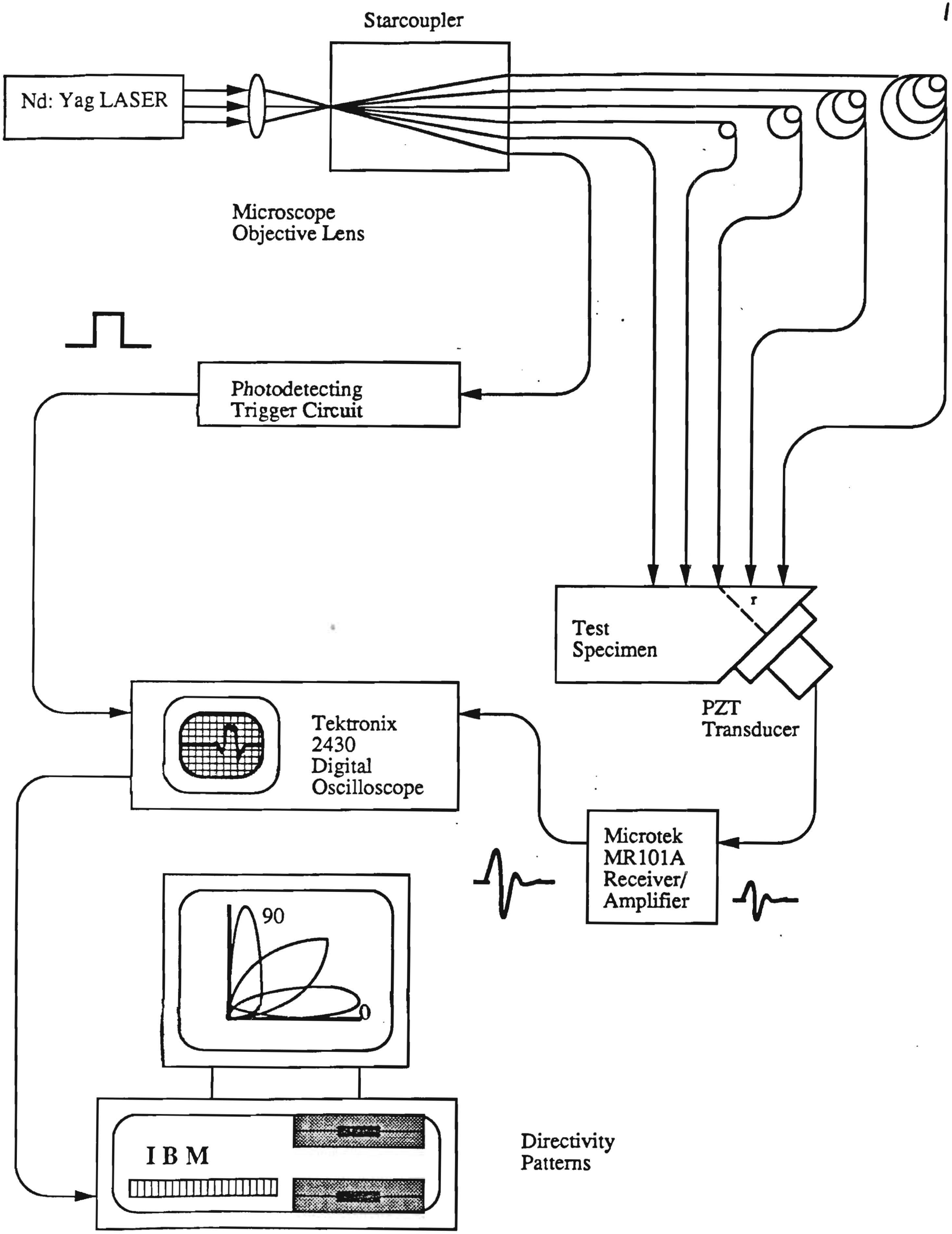
LIST OF FIGURES



Starcoupler
Nd: Yag LASER
Microscope
Objective Lens
Photodetecting
Trigger Circuit
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Test
Specimen
PZT
Transducer
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Digital
Oscilloscope
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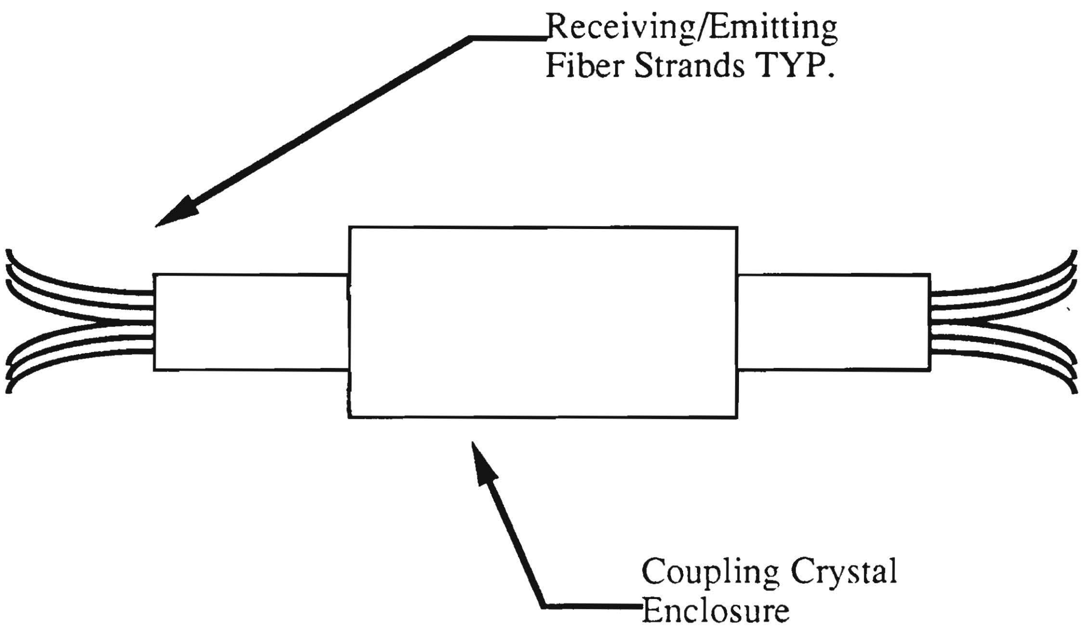
Directivity
Patterns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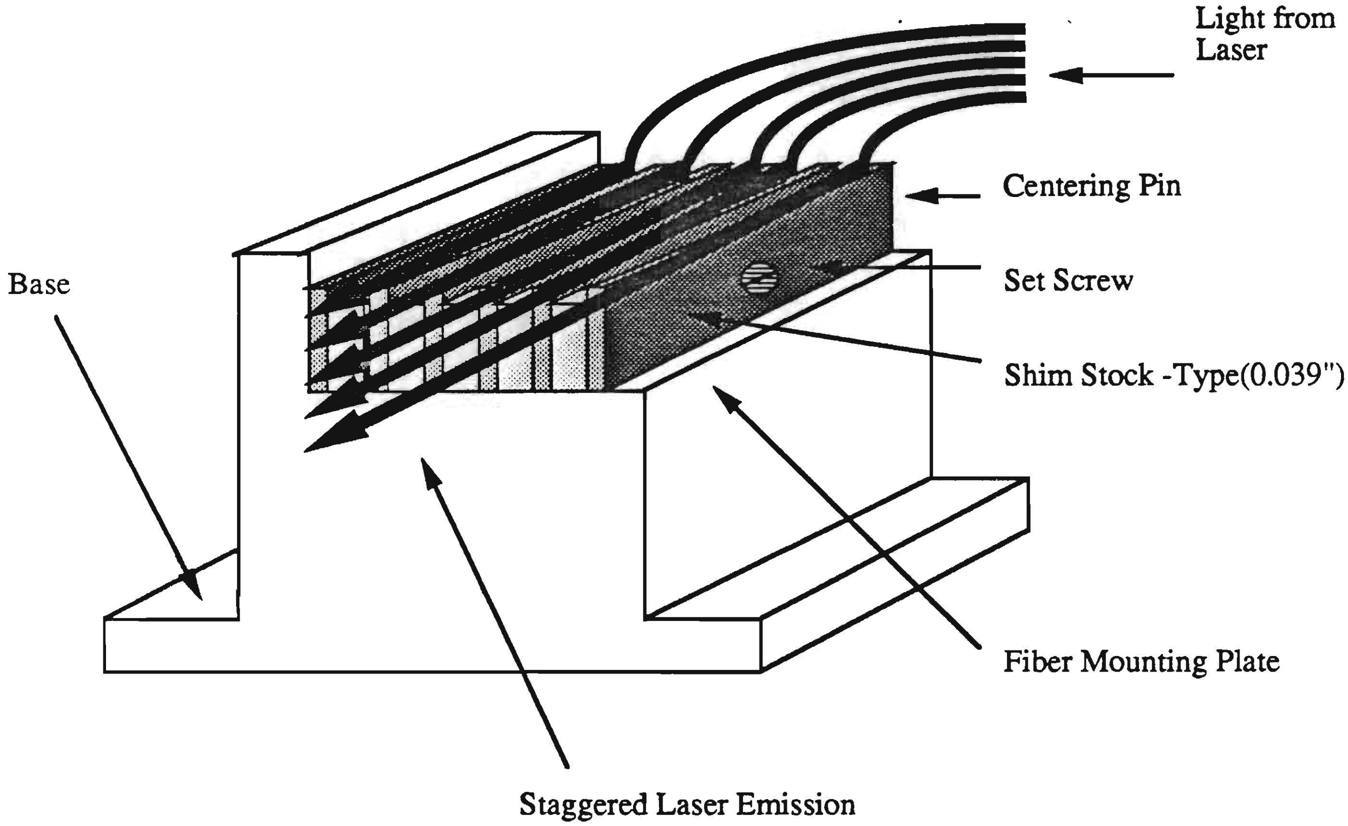
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Fiber Mounting Plate
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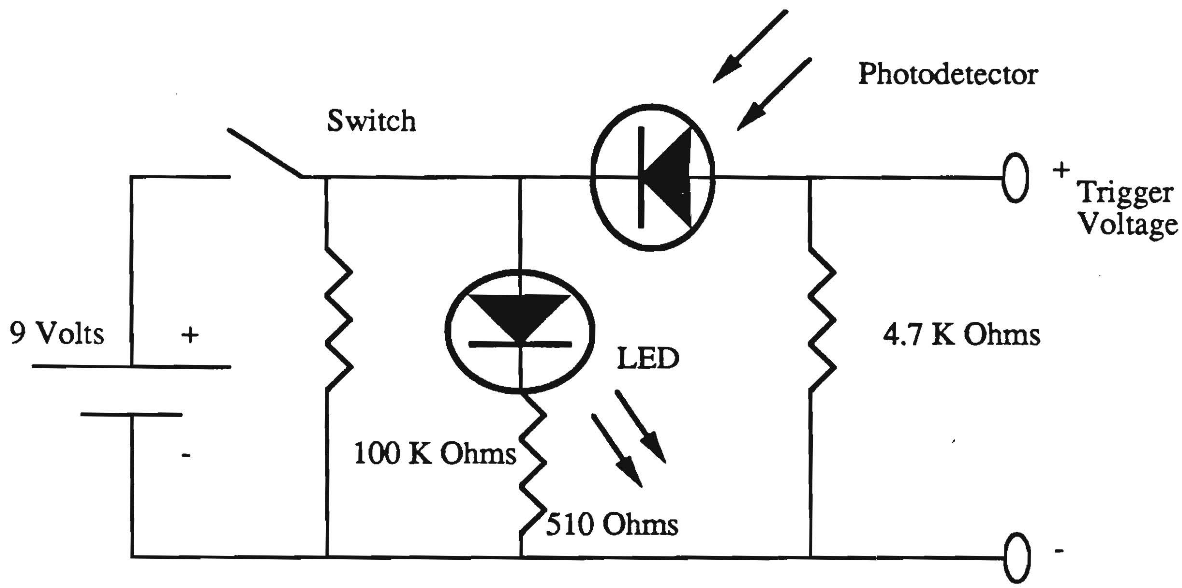
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+
Trigger
Voltage
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+
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LED
-
100 K Ohms
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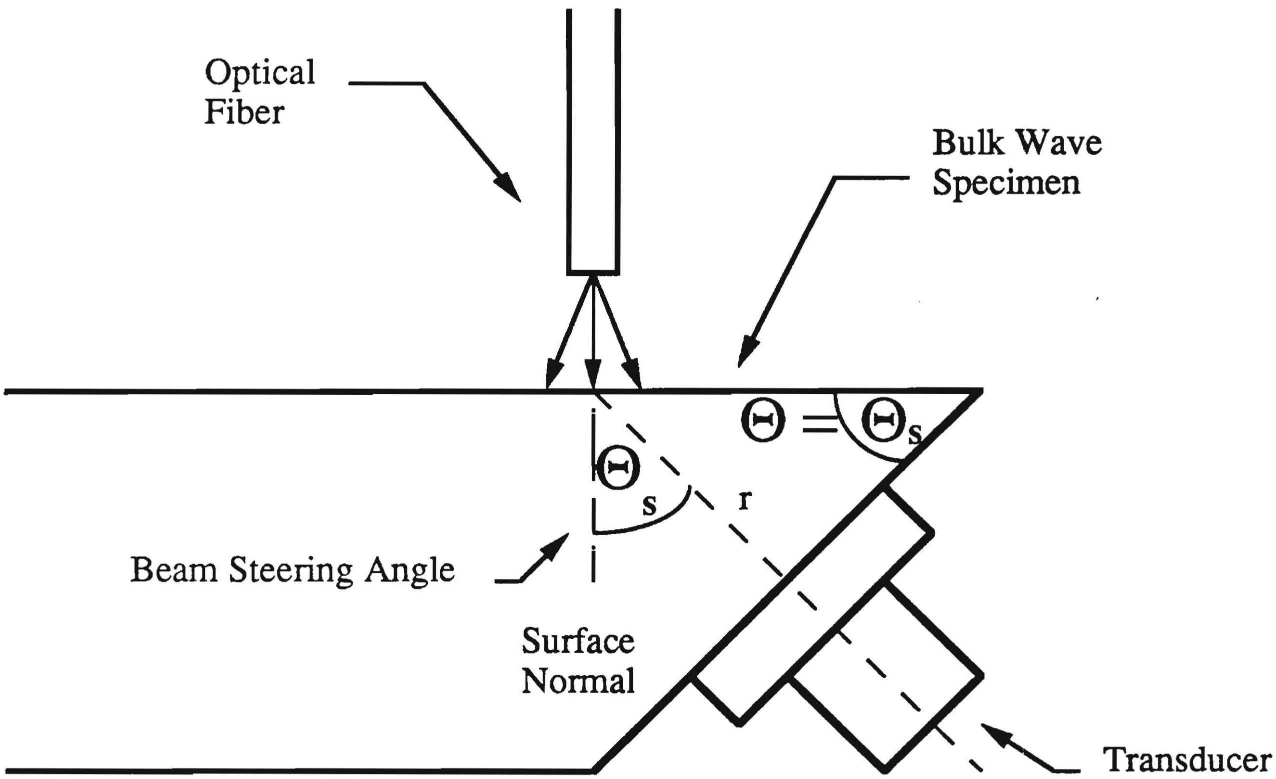
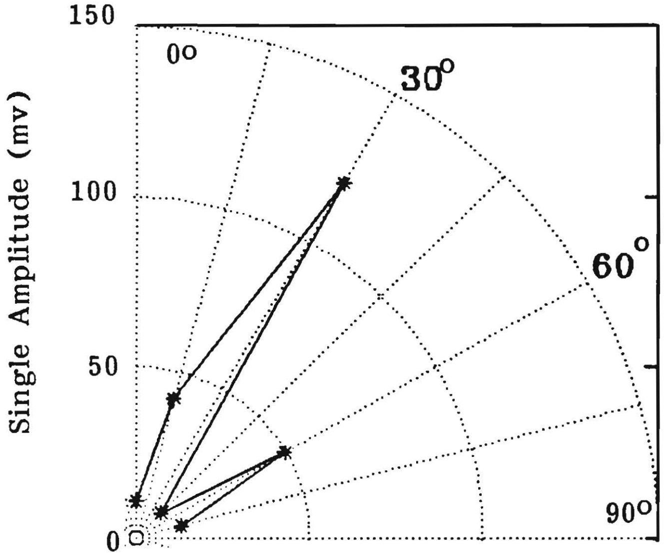
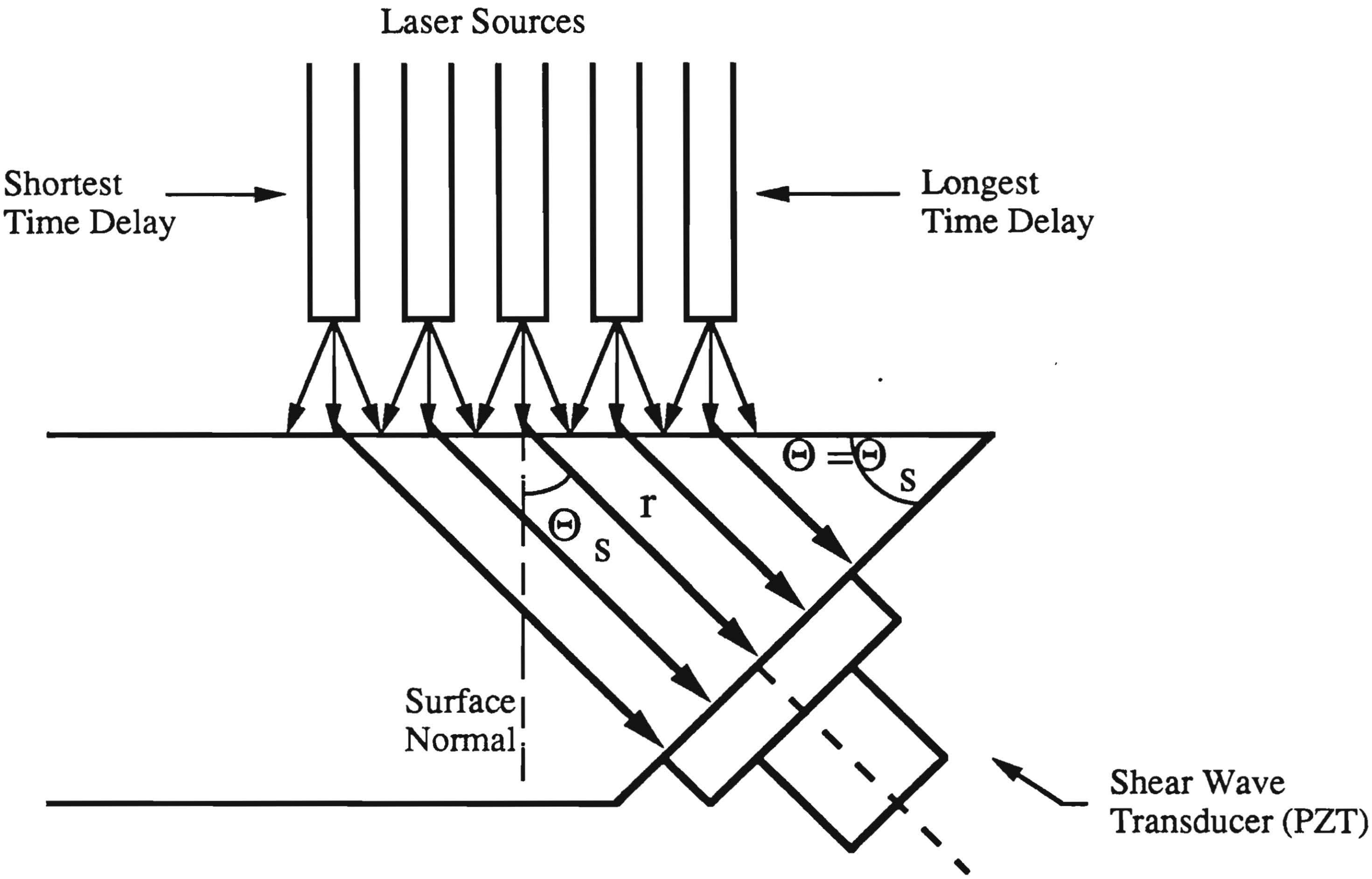
-

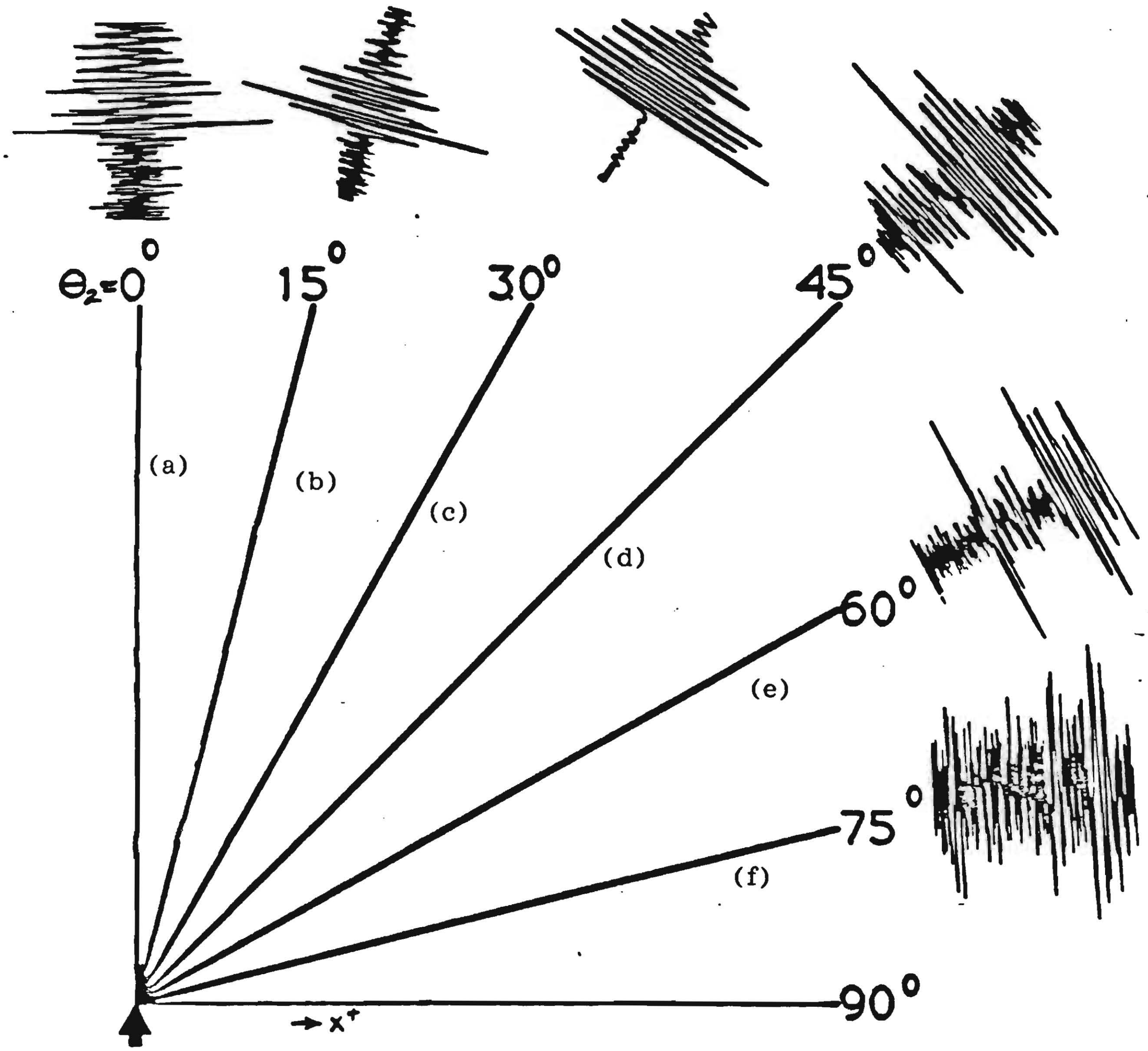


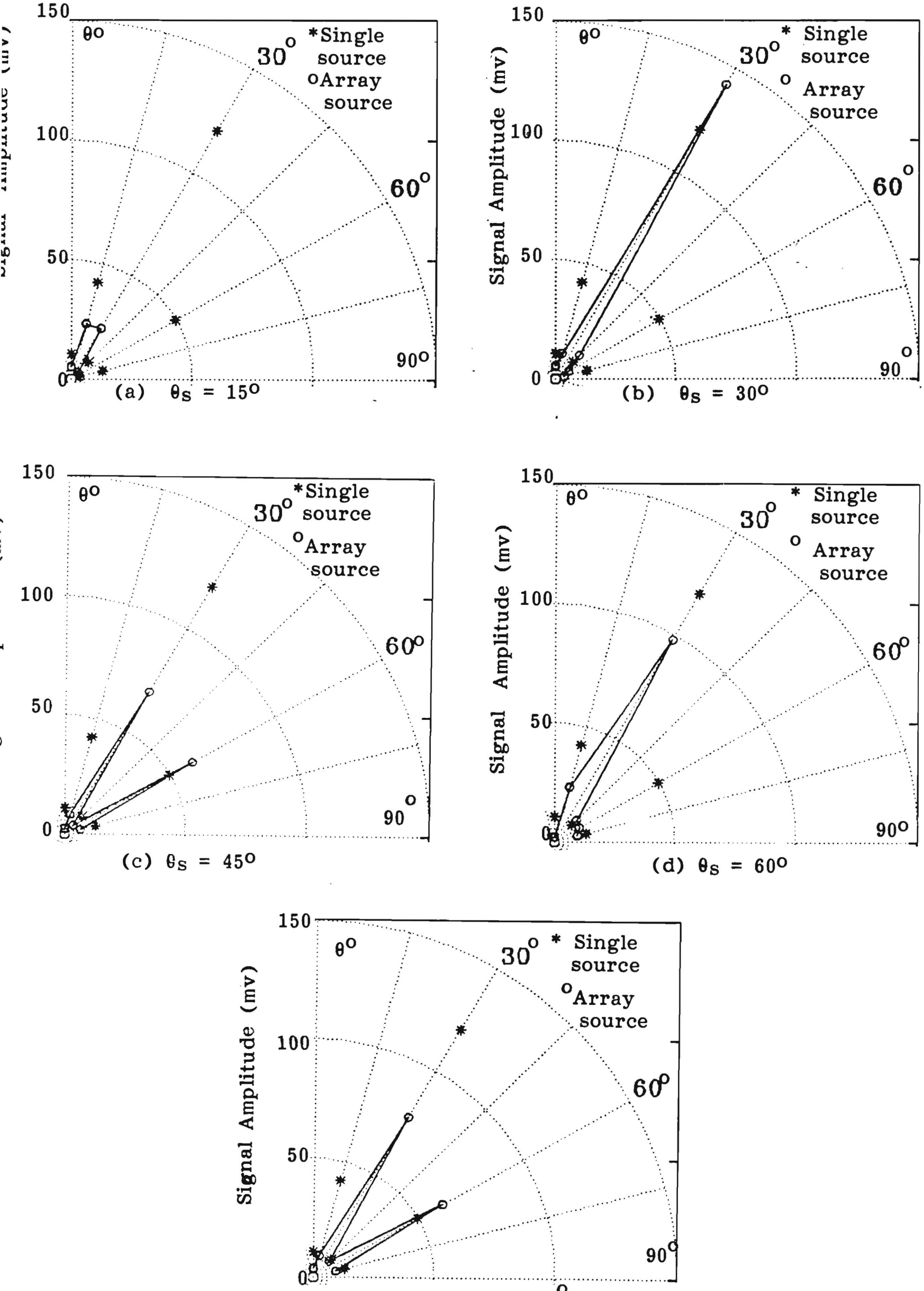
Optical
Fiber
Bulk Wave
Specimen
Θ = Θs
Θs
r
Beam Steering Angle
Surface
Normal
Transducer


150
100
50
0
Single Amplitude (mv)
0o
30o
60o
90o



Laser Sources
Shortest Time Delay
Longest Time Delay
Θ = Θ s
r
Θ s
Surface Normal
Shear Wave Transducer (PZT)

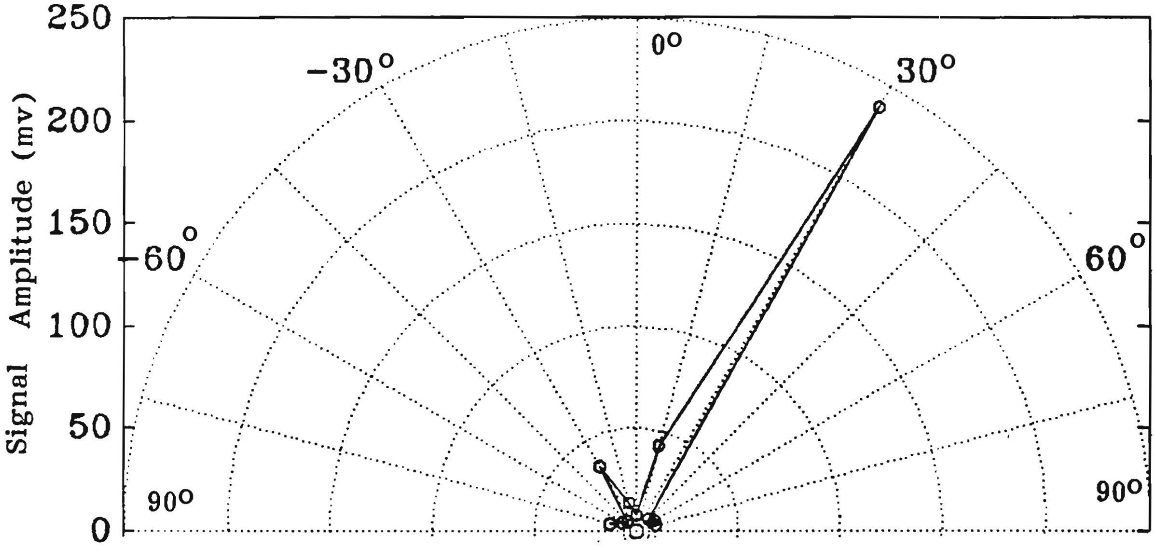

$\theta_2 = 0^0$
15^0
30^0
45^0
60^0
75^0
90^0
(a)
(b)
(c)
(d)
(e)
(f)
$\rightarrow x^+$



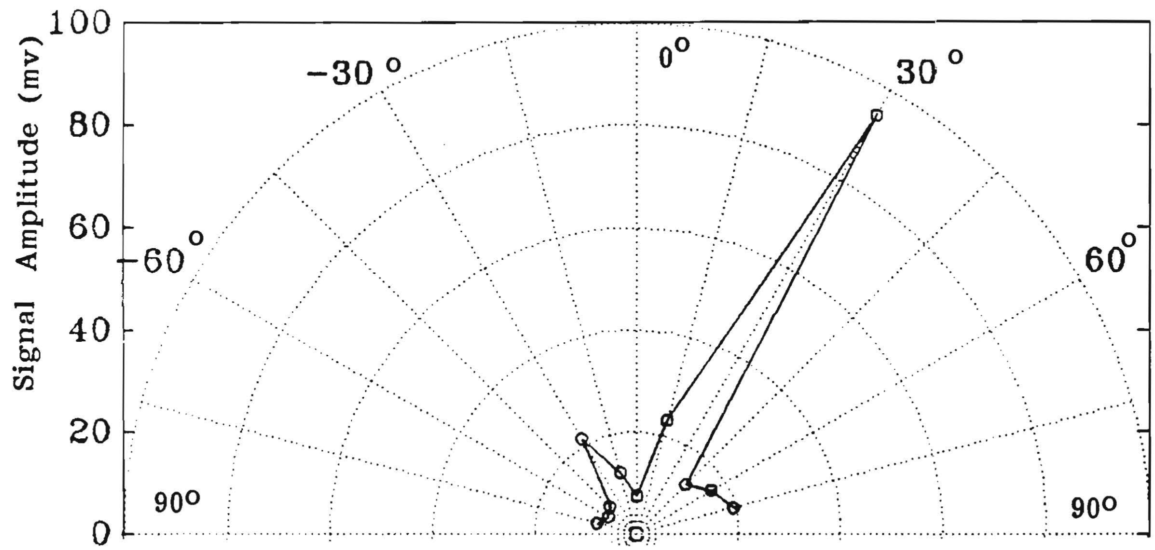
(a) $\theta_S = 15°$ (b) $\theta_S = 30°$

(c) $\theta_S = 45°$ (d) $\theta_S = 60°$

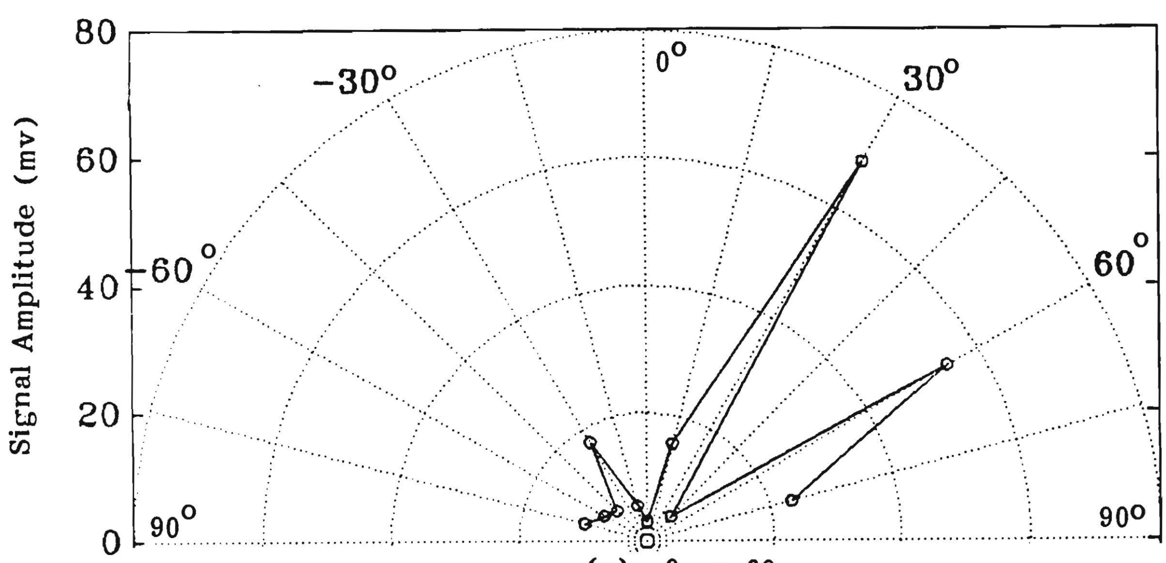
(e) $\theta_S = 75°$



(a) θ_s = 30°.



(b) θ_s = 45



(c) θ_s = 60

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Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

WARD O. WINER
Director

Georgia Institute of Technology
Atlanta, Georgia 30332-0405
(404) 894-3200
Fax: (404) 894-8336

26 May 1992

Dr. Suren Rao, D.
Manufacturing Machines & Equipment
Division of Design and Manufacturing
System's Engineering
National Science Foundation
1800 G. Street, N.W.
Washington, DC 20550

RE: *Continuing Grant Increment "Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control, Grant No. DDM 9001733*

Dear Dr. Rao:

This is to request a continuing grant increment for the above reference proposal. Thank you for your support of the referenced proposal.

Sincerely,

Charles Ume
Associate Professor

CU:bsd

PRELIMINARY REPORT
NSF GRANT NO. DDM-9001733

Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control

Submitted to

Division of Design and Manufacturing
System's ENgineering
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

Submitted by

Charles Ume

GEORGIA INSTITUTE OF TECHNOLOGY

The George W. Woodruff School of Mechanical Engineering
Atlanta, Georgia 30332-0405

May 1992

Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control

This research investigates the use of optical fiber arrays to enhance laser generation of ultrasound. Two major objectives of this research include: (1) The study and development of a noncontact ultrasonic NDE system, with a laser phased array for generating the ultrasound, and an EMAT transducer as a receiver; and (2) A study of the application of the laser phased arrays to on-line control of the depth of weld pool penetration and porosity in a gas metal arc welding (GMAW) process.

Thus far, experimental and numerical directivity patterns have been completed, for optical fiber array, and single fiber generation of longitudinal, shear and surface waves in aluminum and ceramic samples. The results show good agreement between the experimental and numerical results. The longitudinal and shear wave directivity patterns clearly indicate that for inspection purposes, the receiving transducer should be placed at 60° and 30° angles, respectively. Effort is underway to experimentally and numerically generate directivity patterns for a steel sample. Both experimental and numerical directivity patterns for reverse array have also been completed. The results indicated that array enhances sound generation in a forward direction.

There are ongoing research work in the following areas: (1) weld pool simulation; (2) determination of array gain; and (3) signal enhancement in Laser generated ultrasound. The preliminary results obtained thus far are encouraging.

Four graduate students and two undergraduates have been involved in this research since it started. Six technical publications resulting from this work are listed below:

Umeagukwu, C., DeRidder, N., Yang, J., and Jarzynski, J., "Study of the Directivity Patterns of Laser-Optical Fiber Generated Ultrasound," Invited Paper, 121st Meeting of the JASA, Vol. 89, No. 4, Pt. 2, Baltimore, Maryland, April 1991.

Umeagukwu, C., and Jarzynski, J., "Laser Phased Array Generation of Ultrasound with Application to On-Line Nondestructive Weld Quality Control," NSF Design and Manufacturing Systems Grantees Conference, University of Texas, Austin, Texas, January 1991.

Umeagukwu, C., DeRidder, N., Yang, J., and Jarzynski, J., "Laser-Fiber Optic Generation of Ultrasound for Industrial Applications," ASNT Spring Conference, Oakland, California, March 18-22, 1991.

Yang, J., Ume, C. and Jarzynski, J., "Study of the Directivity Patterns of Laser-Optical Fiber Generated Ultrasound in Ceramic Blocks," Invited Paper, SEM Spring Conference, Las Vegas, June 1992.

Yang, J., DeRidder, N., Ume, C., and Jarzynski, J.,"Noncontact Optical Fiber Phased Array Generation of Ultrasound for Nondestructive Evaluation of Materials and Processes," NSF Design and Manufacturing Systems Grantees Conference, Georgia Tech, Atlanta, Georgia, January 1992.

Yang, J., DeRidder, N., Ume, C., and Jarzynski, J., "Noncontact Optical Fiber Phased Array Generation of Ultrasound for Nondestructive Evaluation of Materials and Processes," accepted, Ultrasonics, 1991.

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OMB Number 345-0058
NATIONAL SCIENCE FOUNDATION
1800 G STREET, NW
WASHINGTON, DC 20550

PI/PD Name and Address

Charles Umeagukwu
Mechanical Engineering
GA Tech Res Corp - GIT
Atlanta, Georgia 30332-0405

NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION	
1. **Program Official/Org.** Warren R. DeVries	
2. **Program Name** Manufacturing Processes and Equipment Prog.	
3. **Award Dates (MM/YY)** From: 9/90	To: 8/94
4. **Institution and Address** Georgia Tech Res Corp - GIT Administration Building Atlanta, GA 30332	
5. **Award Number** DDM 9001733	
6. **Project Title** Laser Phased Array Generation of Ultrasound for On-Line Weld Quality Control	

This Packet Contains
NSF Form 98A
and 1 Return Envelop

** Publications Resulting From This Research

1. Yang, J., N. DeRidder, C. Ume, and J. Jarzynski, "Noncontact Optical Fiber Phased Array Generation of Ultrasound for Nondestructive Evaluation of Materials and Processes," Ultrasonics, Vol. 31, No. 6, pp.387-394, November 1993.
2. Yang, J. and C. Ume, "Performance Evaluation of Fiber Array for NDE Application," in press, Research in Nondestructive Evaluation, Vol. 5, No. 3, pp. 175-190, May 1994.
3. Graham, G., J. Yang, C. Ume, "Laser Ultrasound Directivity in CS-3 Ceramic," in press Materials Evaluation, Vol. 52/No. 5, pp. 607-610, May 1994.
4. Pierce, S., C. Ume, and J. Jarzynski, "Signal Enhancement in Laser Generated Ultrasound for Nondestructive Testing," in press, Ultrasonics, January 1994.
5. Yang, J., G. Graham, C. Ume, J. Jarzynski, "Laser Phased Array Generated Ultrasound for Nondestructive Evaluation of Ceramic Materials," accepted, Journal of Nondestructive Evaluation, February 1994.
6. Yang, J., T. Sanderson, G. Graham, and C. Ume, "Laser Phased Array Measurement of Simulated Solidified Weld Penetration Depth," in press, ASME Journal of Engineering in Industry, April 1994.
7. Sanderson, T., Ume, C., and Jarzynski, J., "Second Sound Effects in Dynamic Thermoelasticity Reconsidered," submitted, ASME Journal of Applied Mechanics, January 1995.
8. Sanderson, T. and Ume, C., "Second Sound Effects in Laser Ultrasonics," in preparation. To be submitted to the Journal of Applied Physics.
9. Graham, G., and C. Ume, "Data Acquisition System for Laser Generated Ultrasound," 1994 ASME/ISCIE Japan-U.S.A. Symposium on Flexible Automation.
10. Umeagukwu, C., and J. Jarzynski, "Laser Phased Array Generation of Ultrasound with Application to On-Line Nondestructive Weld Quality Control," NSF Design and Manufacturing Systems Grantees Conference, University of Texas, Austin, Texas, January 1991.
11. Umeagukwu, C., N. DeRidder, J. Yang, and J. Jarzynski, "Study of the Directivity Patterns of Laser Optical Fiber Generated Ultrasound," Invited Paper, 121st Meeting of the JASA, Vol. 89, No. 4, Pt. 2, Baltimore, Maryland, April 1991.
12. Yang, J., G. Graham, M. Timmerman, C. Ume, and J. Jarzynski, "Study of the Directivity Patterns of Laser-Optical Fiber Generated Ultrasound in Ceramic Blocks," Invited Paper, SEM Spring Conference, Las Vegas, June 1992.
13. Yang, J., N. DeRidder, C. Ume, and J. Jarzynski, "Noncontact Optical Fiber Phased Array Generation of Ultrasound for Nondestructive Evaluation of Materials and Processes," NSF Design and Manufacturing Systems Grantees Conference, Georgia Tech, Atlanta, Georgia, January 1992.
14. J. Yang and C. Ume, "Optical Fiber Phased Array Generation of Ultrasound for Process Control," Joint US-Taiwan Symposium on Advanced Manufacturing Processes, Ga. Tech., Atlanta, Georgia, February 10-11, 1993.
15. C. Ume, "Laser/Optical Fiber Phased Array Generation of Ultrasound for On-Line Weld Quality Control," NSF Desgin and Manufacturing Systems Grantees Conference, UNC Charlotte, NC, January 6-8, 1993.
16. C. Ume, "Laser/Optical Fiber Phased Array Generation of Ultrasound for NDE of Materials and Processes," Ford Motors Material Systems Reliability, November 19, 1992.
17. Ume, C., and Graham, G., "Laser Phased Array Generation of Ultrasound for On-Line Weld Quality control: Predicted and Measured Array Gain," NSF Design and Manufacturing Grantees Conference, MIT, Boston, Massachusetts, January 5-7, 1994.
18. Yang, J., Sanderson, T., Graham, G., and Ume, C., "Ultrasonic Weld Penetration Depth Sensing with a Laser Phased Array." ASME International Mechanical Engineering Congress and Exposition. Chicago, IL. November 11-14, 1994.
19. Graham, G.M., "Intelligent Welding with Laser Ultrasonic Sensing," The First World Congress on Intelligent Manufacturing Processes and Systems, Mayaguez, Puerto Rico, February 13-17, 1995.
20. Sanderson, T.M., Graham,G.M, Ume, C.I. and Jarzynski, J., C.I. Ume, "Comparison of Laser Ultrasonic Source Models for Weld Quality Control." Submitted 4th International Conference on Trends in Welding Research. Gatlinburg, TN. June 5-9, 1995.
21. Graham, G.M., Sanderson, T.M., and Ume, C., "Laser Array Generated Ultrasound for Weld Quality Control." Submitted 4th International Conference on Trends in Welding Research. Gatlinburg, TN. June 5-9, 1995.

PART IV – FINAL PROJECT REPORT – SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	2				7	1	5			
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native					1					
Asian.										
Black, Not of Hispanic Origin.										
Hispanic					1					
Pacific Islander										
White, Not of Hispanic Origin					5	1	5			
C. Total, Other Non-U.S. Citizens			1		3					
Specify Country 1. Taiwan					1					
2. Pakistan					1					
3. China			1							
D. Total, All participants (A + B + C)	2		1		10	1	5			
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.